Journal of Equine Veterinary Science 149 (2025) 105567

Contents lists available at ScienceDirect

Journal of Equine Veterinary Science

journal homepage: www.elsevier.com/locate/jevs

Review Article

The application of the pyramidal training model for conditioning thoroughbred horses

Allan Davie [a], Rosalind Beavers [b], Joshua Denham [c,d,*]

[a] Australian Equine Racing and Research Centre, Ballina, New South Wales, 2478, Australia
[b] Faculty of Health Sciences, Southern Cross University, East Lismore, New South Wales, 2480, Australia
[c] School of Health and Medical Sciences, University of Southern Queensland, Ipswich,4305, Queensland, Australia
[d] Centre for Health Research, Toowoomba, Queensland, 4350, Australia

ARTICLE INFO

Keywords:
Aerobic training
Blood lactate
Performance
Periodization
Racehorse

ABSTRACT

The purpose of this review was to analyze the scientific background and practical application of a very successful human training methodology, the pyramidal training model, to the Thoroughbred racehorse. Despite years of research and accumulated knowledge on human training methods to enhance endurance performance, Thoroughbred training programs have lacked significant change. This review introduces the pyramidal training model, explains the science that underpins this training concept and outlines one approach to translate this science into the equine field. It also discusses the importance of training load and provides insight into the monitoring of the load and psychophysiological stress level of the horse during training. The use of heart rate and blood lactate responses to exercise is encouraged to guide exercise training sessions. These responses are the best indices of internal load, and the most accurate measure of effort in horses. Applying this information can help provide the desired training stimulus and overall training workload to maximize endurance performance.

1. Introduction

Despite years of research and accumulated knowledge now available from a data-driven world, the horseracing industry has been slow to embrace technologies that have already become mainstream in many sports [1,2]. The technology to monitor horses' training workloads (heart rate, GPS data and lactate) is widely available for trainers, yet the evidence-based scientific application of these methods is underutilized.

The purpose of this review was to introduce the pyramidal training model (PTM) and encourage this method for exercise training Thoroughbred racehorses. Although the PTM could be successfully applied to other breeds and racing formats, a comprehensive review on the science and how the PTM could be applied to all breeds of horses would be outside the scope of this work. This work explains the science that underpins this training concept and outlines one approach to translate this science into Thoroughbred racing. It is also anticipated that the article encourages others to examine the utility of the PTM in other equine athletes (i.e., Arabian, Quarter horses, etc.) and competitive events.

Exercise involves repetitive muscle contractions that provoke physiological responses and ultimately adaptations following repeated bouts of training. The nature and magnitude of training adaptations are a culmination of many factors including: the structure of the training protocol (i.e., stimulus), the recovery period and an adaptive phase in which the muscle regains homeostasis [3]. This return to homeostasis is governed by both physiological and other biological factors occurring at different rates, depending on the training history, exercise load and environmental circumstances (e.g., heat, humidity, simulated altitude [hypoxia], etc.).

The PTM has gained popularity among elite endurance and middle-distance human athletes and is a training method aimed at maximizing adaptations and endurance performance. The PTM dictates that the majority of training is conducted at low intensity (70–80 % of total volume of work), while 20–30 % of the total training volume is performed at moderate to high intensities [4–6] with more completed at the moderate than the highest intensity (Fig. 1). The training stimulus that is applied is a combination of the intensity, duration and frequency of the training stimuli, which results in the desired physiological adaptations to enhance endurance performance.

Research has highlighted the importance of the prescribed training workload as a key factor in stimulation of adaptations [7]. The training workload is the physiological and psychological stress that the body experiences in response to a training stimulus, which is a combination of

* Corresponding author.
E-mail address: Josh.Denham@unisq.edu.au (J. Denham).

https://doi.org/10.1016/j.jevs.2025.105567
Received 12 October 2024; Received in revised form 8 April 2025; Accepted 8 April 2025
Available online 9 April 2025

the frequency, intensity and duration of the exercise (i.e., stimulus) that can include intermittent recovery periods between intervals. The workload can be broken down into an external and internal component [8]. The external component encompasses volume and intensity, which is the distance covered and the speed at which it is covered. The internal load is the psychophysiological response that the load initiates to cope with the external load [7] and is considered the major gauge of adaptation. Heart rate (HR) and blood lactate (BLa) responses to exercise training are considered the best indices of internal load and are the most accurate measures of effort used to guide exercise prescription [8,9]. Although determining the psychological impact of training remains challenging in the horse, measuring the internal training load (i.e., HR and BLa) during each exercise training session and applying that information to elicit the desired overall training workload, is arguably a critical component of exercise prescription. Indeed, different training models, including PTM, polarized and lactate threshold, that use HR and BLa to monitor training, have been successfully adopted in elite endurance runners and cyclists for decades [7,10].

2. The scientific foundations supporting the utility of the PTM

Research has shown that following the PTM guidelines during training leads to a sustained increase in cardiac output over a prolonged period of time, ultimately resulting in physiological adaptations that improve oxygen delivery and increase the capacity for oxidative metabolism [7]. The increased oxidative capacity of the working muscles is correlated to increased mitochondrial biogenesis (i.e., content) and function, and capillarization in type I (slow-twitch fatigue-resistant) skeletal muscle fibres [11].

The process of mitochondrial biogenesis requires coordinated regulation of encoded genes from the nuclear and mitochondrial genomes. Indeed, peroxisome proliferator-activated receptor gamma coactivator 1-alpha (PPARGC1A) is capable of co-activating the nuclear and mitochondrial genes required for mitochondrial synthesis. The encoded protein, PGC-1α, is the widely accepted "master regulator" of mitochondrial biogenesis induced in skeletal muscle in the hours following a single bout of exercise [12]. In skeletal muscle the two primary signaling pathways for PGC-1α activation and mitochondrial proliferation are calcium signaling and adenosine monophosphate (AMP)-activated protein kinase (AMPK) [13]. While the calcium signal is more likely used with lower intensity high-volume training, the AMPK pathway is stimulated with high-intensity training, as adenosine triphosphate (ATP) and AMP levels are reduced and increased, respectively. The adaptive potential of the calcium signaling pathway is much larger than that of the AMPK signaling pathway. Coyle (1984) [14] proposed that the magnitude of the increase in mitochondria is influenced by the duration of the exercise or training session, which has been supported by more recent work by Bishop et al. (2019) [11] who also demonstrated that the volume of training is more important than intensity for increasing mitochondrial content. This does not distract from the importance of intensity, as it has been proposed that intensity also stimulates improvements in mitochondrial function [15]. There is, however, not a direct linear relationship, as with additional training this factor becomes less critical.

In the equine field, Tyler et al. (1998) [16] reported that the mitochondrial volume/density continued to increase over 34 weeks of training and paralleled the increase in VO_{2max} in two groups of horses (control and overload training). The overload trained horses exercised at higher intensities but did not differ from control horses in mitochondrial density or other skeletal muscle adaptations following 34 weeks of training. This study supports the research in humans that longer moderate intensity exercise is the key stimulus for development of oxidative capacity and muscle physiological adaptations to exercise [16]. Mitochondrial density and metabolic efficiency are important components of stamina, both of which were reported to increase in parallel with VO_{2max} improvements, which supports the concept of reducing the volume of high intensity work. A reduction in high intensity work, as described in the PTM, may also decrease the risk of orthopedic injuries, as excessive use of high-speed 'fast days' is a major risk factor of catastrophic musculoskeletal injuries in racehorses [17]. This finding encourages the sparing use of fast days (i.e., exercise performed in zone 3), particularly in close succession without adequate recovery with low intensity training – consistent with the PTM.

Homeostatic disturbances and high physiological stress can interfere with adaptation and may lead to failure of the muscle to respond favourably to the training [10], which reinforces the need for training to be closely monitored. This state can lead to overreaching or overtraining syndrome, which if the situation progresses can be associated with a sustained decreased in performance [18,19]. Overreaching and overtraining occur due to excessive exercise or stress and/or inadequate recovery. Overreaching has been described as functional and non-functional states [20], with functional being a short term state and non-functional resulting in extended periods of impaired performance. Overtraining, however, is considered severe non-functional

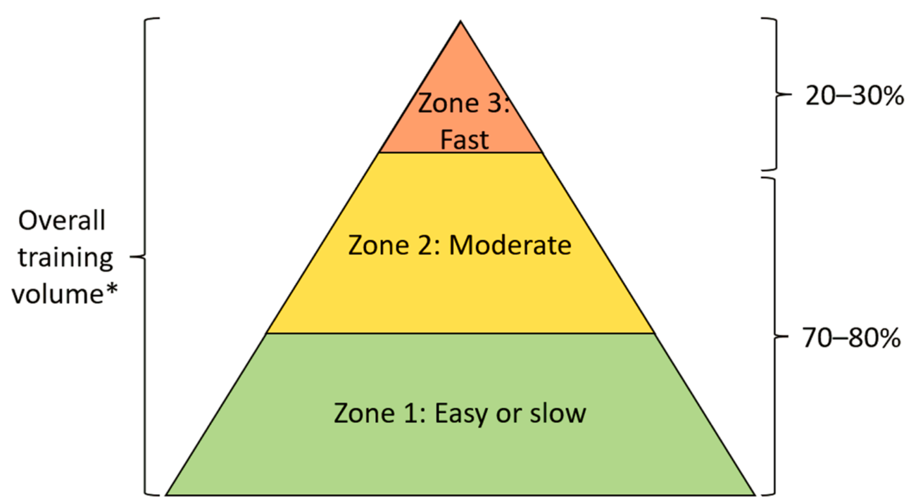

Fig. 1. Diagram illustrating the Pyramidal training model adapted for the equine athlete in which the overall training volume is divided into three training zones based on heart rate and blood lactate responses to training and recovery periods. Zone 3 is used sparingly, as this zone equates to high-speed or fast work which is 600 m and 800 m gallops at differing speeds. Most training (70–80 %) is reserved for slow to moderate intensity efforts (Zone 1 and 2) comprised of controlled treadmill gallops plus walking, trotting and cantering. *The overall training volume relates either to the weekly training volume or daily exercise training volume.

overreaching that results in a prolonged performance decrement and more severe symptoms that impede performance and requires an extended recovery period [20].

Inflammatory responses and slow autonomic recovery following high intensity training have been related to a failure to adapt [21,22]. The measure of the internal load (HR and BLa) is one indicator of physiological stress. Seiler et al. (2006) [10] considered that the adaptation in response to exercise is very much influenced by the level of physiological adjustment to the demands of the exercise or stress generated, and that the physiological adjustments are an attempt to restore homeostasis. Therefore, the physiological adjustments reflect the physiological stress. Importantly, physiological stress must be carefully monitored and controlled. An ideal amount of stress can instigate desirable adaptations to the muscle or body systems. Conversely, too much stress negatively affects the muscle's capacity to adapt and extends recovery time. While controlling the physiological stress level is paramount to any training, it is crucial following high intensity training, typical in Thoroughbred training. Importantly, the level of recovery between high intensity gallops is critical to the capacity of the muscle to respond to the next gallop.

Heart rate and BLa responses provide a comprehensive assessment of post-exercise recovery, as they reflect both cardiovascular and metabolic responses. Human studies suggest that faster HR and BLa recovery after the cessation of exercise demonstrates superior exercise performance and cardiorespiratory fitness [23,24]. The use of HR measurements for predicting performance and training adaptations is based on a linear relationship between HR and workload up until VO_{2max}. The major advantage of using HR rate as a predictor of endurance performance is that it is relatively cheap, and easy to administer (e.g., via a HR girth belt) and continuously monitor (e.g., via a trainer wrist-worn watch or smart phone). Further, as with any measure, it is essential that the methodology and equipment used are standardized, as well as valid and reliable.

The mechanisms controlling HR changes at the start, during and following exercise are well documented and their value in the assessment of physiological adaptations from different training regimens has been realized in both human and equine athletes [25]. The Thoroughbred racehorse competes in events ranging from 1000 m to 4000 m plus, and must sustain a high oxygen delivery to the working muscles, including both locomotive and respiratory. This is achieved predominantly by their ability to increase cardiac output from resting levels of around 32–49 $L{\cdot}min^{-1}$ to approximately 300 $L{\cdot}min^{-1}$, and achieve a relative VO_{2max} in the range of 154 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ during maximal efforts [26].

All parameters of cardiac function, including HR, conduction, force of contraction and relaxation, reflect the net balance between an inhibitory parasympathetic influence and an excitatory sympathetic influence [27]. Therefore, cardiac parasympathetic reactivation could be considered the principal determinant of the immediate fall in HR when exercise ceases or intensity drops. Horses' recovery HRs (HR_{rec}) decrease in a bi-exponential manner, with a faster initial and a slower secondary decrease [28]. An athletes' HR_{rec} is normally measured during the immediate recovery period following a bout of exercise or training interval (e.g., the first few minutes after the cessation of training), and is often expressed as the difference between peak exercise HR and HR at specific time intervals during recovery [29]. The HR_{rec} can be influenced by the exercise intensity, duration, and individual cardiorespiratory fitness level. A faster HR_{rec} following high-intensity exercise may indicate an efficient autonomic nervous system functioning (e.g., vagal tone) and cardiorespiratory fitness [30]. Horses with quicker HR_{rec} may be capable of sustained efforts and quicker recovery between bouts of exercise [31]. Slower HR_{rec} may suggest prolonged sympathetic activation or inadequate cardiovascular adaptation to the exercise stress. Thus, combining HR_{rec} with other recovery markers, such as BLa concentrations, provides a simple and effective means to assess post training recovery.

Post exercise BLa concentrations reflect muscle metabolic activity, recovery and performance. In humans, the relationship between BLa concentration and exercise has been extensively studied, and it is commonly used in training [32,33]. The lactate inflection point (LIP) or lactate threshold represents the point when muscle lactate production exceeds its removal, leading to a rapid increase in BLa concentration [34]. Notably, LIP is a strong indicator of one's ability to sustain high-intensity exercise and endurance performance in human and equine athletes, such that higher running speeds at LIP reflect superior endurance performance. Studies have demonstrated correlations between HR_{rec}, LIP, and performance in horses [35,36]. Horses with superior HR_{rec} and higher LIP tend to exhibit superior endurance capabilities and overall performance in disciplines requiring sustained effort, such as long-distance racing (50-100 km) and eventing [37,38].

Therefore, monitoring and interpreting these physiological markers has the potential to help tailor individualized training programs to improve cardiorespiratory fitness in horses. It is reasonable to suggest that equine training programs aimed at improving HR_{rec} and raising the speed corresponding to the LIP would enhance horses' endurance performance. Although HR_{rec} and LIP can provide valuable insights into performance potential, they only form part of the complete composite of factors that underpin endurance and race performance (e.g., nutrition, recovery, overall health, etc.).

3. Background and a potential method for the application of the pyramidal training model for the Thoroughbred horse

The application of the PTM requires the organization of training into separate zones. Specifically, exercise is performed below the lactate threshold intensity for 70–80 % of the weekly training volume (time or training distance) (zones 1 and 2), and above the lactate threshold intensity for the remaining 20–30 % of the weekly training volume (zone 3). Although organizing the training intensity continuum into specific zones is common in humans, it may prove more problematic in horses. In humans, the zones are arranged by physiological variables such as a percentage of maximum HR or VO_{2max}, BLa concentrations or ventilatory thresholds. Low intensity training 'zone 1' is considered at BLa concentrations of 1-2 $mmol{\cdot}L^{-1}$, moderate intensity 'zone 2′ at 2–4 $mmol{\cdot}L^{-1}$ and high intensity training (zone 3) at > 4 $mmol{\cdot}L^{-1}$ [5,39]. To date, the application of lactate guided training has been applied sparingly to the equine field, yet studies suggest that a lactate-guided conditioning program can significantly enhance endurance performance [40–43].

Accordingly, measuring internal training load (i.e., HR and BLa) and using this information to control the relative training intensity (i.e., speed) and for adjusting the frequency, duration and number of intervals, may optimize the desired training stimulus. To establish a training workload or stimulus for Thoroughbred horses that is representative of a similar stress level used by humans in the PTM, the maximum lactate steady state (MLSS) data from athletes was compared to Thoroughbred studies. The MLSS is defined as the highest BLa concentration that can be maintained over an extended period of time without a continual increase in BLa concentration [44]. In humans, a close relationship between endurance performance and MLSS has been reported [45]. However, the MLSS determination method is not easy to implement in the racehorse's training schedule, as MLSS protocols require three constant-velocity exercise sessions of approximately 30 min on separate days. Therefore, a more appropriate procedure, which require a single exercise session, such as the D-max or a modified version of the MLSS, the lactate minimum speed test (LMS) [46,47] could be more appropriate for MLSS prediction in equine athletes. The D-max (see description in text) is an accurate and reliable measure of the MLSS and endurance performance in human athletes [48]. The LMS test is also a valuable test for predicting performance and designing individualized training programs. Ramos et al. (2024) [43] described a treadmill version of the LMS test as having three steps, a hyperlactatemia induction step, active recovery and an incremental exercise test. The hyperlactatemia step involves working on the treadmill on a 6 % incline and a speed of 10 $m{\cdot}s^{-1}$ for 120 s. Following the gallop, the horse has an active recovery with the treadmill in a horizontal position at a speed of 1.7 $m{\cdot}s^{-1}$ for 120 s. The horse then performs an incremental exercise test at a 6 % incline with an initial speed of 3.0 $m{\cdot}s^{-1}$ for 4 min and 27 s. Each subsequent increase in speed is 0.5 $m{\cdot}s^{-1}$. The time periods at each speed are adjusted to ensure every stage is 800 m. For example, 3.5 $m{\cdot}s^{-1}$ for 3 min and 49 s; 4.0 $m{\cdot}s^{-1}$ for 3 min and 20 s; 4.5 $m{\cdot}s^{-1}$ for 2 min and 58 s; 5.0 $m{\cdot}s^{-1}$for 2 min and 40 s; 5.5 $m{\cdot}s^{-1}$ for 2 min and 26 s; 6.0 $m{\cdot}s^{-1}$ for 2 min and 13 s; 6.5 $m{\cdot}s^{-1}$ for 2 min and 3 s; 7.0 $m{\cdot}s^{-1}$ for 1 min and 54 s; and 7.5 $m{\cdot}s^{-1}$ for 1 min and 47 s. To determine BLa concentrations and speed representative of LMS a second order polynomial curve is fitted to the BLa versus speed data. Speeds at the LMS test range from 4.7 to 6 $m{\cdot}s^{-1}$ [43] and approximately 7 $m{\cdot}s^{-1}$ [47] for Arabians and Standardbreds respectively.

Although the utility of the D-max method has not been examined in horses, the concept can be applied to any lactate curve, provided standardized testing protocols are followed to determine the LIP. The D-max method simply involves measuring the lactate responses to an incremental exercise treadmill test, and representing lactate response as a second-order polynomial regression curve. The D-max is defined as the point on the regression curve that yields the maximal distance to the straight line formed by the two end points of the curve.

In Fig. 2, the incremental exercise test protocol involved horses exercising for 2 mins at 4 $m{\cdot}s^{-1}$, after which the treadmill speed was increased by 1 $m{\cdot}s^{-1}$ every 60 secs, until a predetermined fixed set end point or until the horse could no longer maintain their speed safely. The D-max method was applied to the average results of a group of Thoroughbred horses that completed an incremental treadmill test. The D-max point occurred at a lactate concentration of approximately 3 $mmol{\cdot}L^{-1}$ which was represented by a treadmill speed of approximately 8 $m{\cdot}s^{-1}$ at 6° incline. The speed of 8 $m{\cdot}s^{-1}$ for Thoroughbred racehorses is aligned with that reported for Arabian horses of 4.7 to 6 $m{\cdot}s^{-1}$ [43,49] and Standardbreds of approximately 7 $m{\cdot}s^{-1}$ [47].

Therefore, the application of the PTM to Thoroughbred training seems viable using the equine treadmill, as speed, intensity and workload can be controlled to provide the desired BLa concentration. Gallop distance, speeds and grade can be set based on LMS or D-Max results, to generate BLa levels representative of the LMS or D-max point. Based on the PTM, these gallops would be repeated twice per week (to represent the 70–80 % of training in zone 1 and 2), with a third gallop conducted on the racetrack at speeds close to 70–80 % of maximum or 'race speed' (to represent the 20–30 % of training in zone 3). The use of HR monitors during gallops and assessing HR_{rec} and BLa concentrations post gallop, enables monitoring of stress levels during training, and allows the trainer to adjust treadmill speed and grade in line with improvements in the horse's cardiorespiratory fitness.

4. Conclusion

With the volume of effective, evidence-based training methods successfully used for enhancing endurance performance in human athletes (e.g., PTM) and the translatability of the science that underpins this training concept to the equine athlete, translation of the PTM into the equine field is warranted. The application of the evidence-based training methods to Thoroughbred training seems viable via the treadmill, as speed, intensity and workload can be controlled to provide the desired BLa or HR targets. Technology also permits the monitoring of internal and external training stress and recovery between training sessions. This effective training system is not only designed to tailor exercise training programs to the animal, but also may prevent over-reaching/ overtraining and maximize endurance performance in Thoroughbred racehorses.

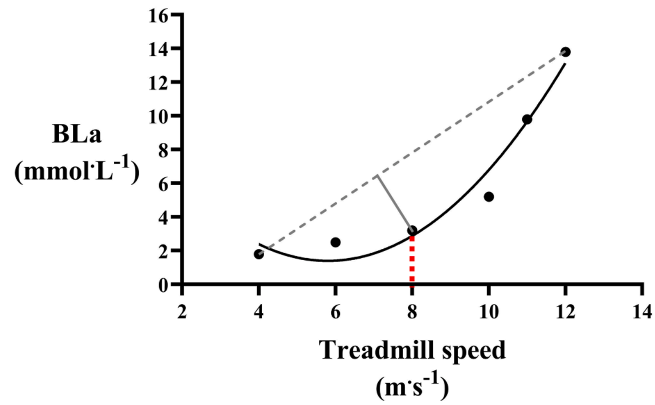

Fig. 2. The D-max method for determining maximum blood lactate (BLa) steady state involves measuring the lactate responses to an incremental exercise treadmill test, and representing the BLa response as a second-order polynomial regression curve. The D-max is defined at the point on the regression curve that yields the maximal distance to the straight line (dotted line) formed by joining the two end points of the curve (in this case 8 $m{\cdot}s^{-1}$).

Ethics

In this review the authors report that to the best of their knowledge this paper is an accurate account of work performed as well as an objective discussion of its significance. The paper is accurate and objective and contains sufficient detail and references to permit others to examine the work.

CRediT authorship contribution statement

Allan Davie: Writing – review & editing, Writing – original draft, Conceptualization. **Rosalind Beavers:** Writing – review & editing, Conceptualization. **Joshua Denham:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

References

[1] Randle H, Steenbergen M, Roberts K, Hemmings A. The use of the technology in equitation science: a panacea or abductive science? Appl Anim Behav Sci 2017; 190:57–73. https://doi.org/10.1016/j.applanim.2017.02.017.
[2] Alysen Miller, Tech advances-opportunities for trainers, (2019).
[3] Furrer R, Handschin C. Molecular aspects of the exercise response and training adaptation in skeletal muscle. Free Radic Biol Med 2024;223:53–68. https://doi.org/10.1016/j.freeradbiomed.2024.07.026.
[4] Casado A, Foster C, Bakken M, Tjelta LI. Does lactate-guided threshold interval training within a high-volume low-intensity approach represent the "next step" in the evolution of distance running training? IJERPH 2023;20:3782. https://doi.org/10.3390/ijerph20053782.
[5] Seiler S. What is best practice for training intensity and duration distribution in endurance athletes? Int J Sports Physiol Perform 2010;5:276–91. https://doi.org/10.1123/ijspp.5.3.276.
[6] Sperlich B, Matzka M, Holmberg H-C. The proportional distribution of training by elite endurance athletes at different intensities during different phases of the season. Front Sports Act Living 2023;5:1258585. https://doi.org/10.3389/fspor.2023.1258585.
[7] Casado A, González-Mohíno F, González-Ravé JM, Foster C. Training periodization, methods, intensity distribution, and volume in highly trained and elite distance runners: a systematic review. Int J Sports Physiol Perform 2022;17:820–33. https://doi.org/10.1123/ijspp.2021-0435.
[8] Dudley C, Johnston R, Jones B, Till K, Westbrook H, Weakley J. Methods of monitoring internal and external loads and their relationships with physical qualities, injury, or illness in adolescent athletes: a systematic review and best-evidence synthesis. Sports Med 2023;53:1559–93. https://doi.org/10.1007/s40279-023-01844-x.

[9] Impellizzeri FM, Marcora SM, Coutts AJ. Internal and external training load: 15 years on. Int J Sports Physiol Perform 2019;14:270–3. https://doi.org/10.1123/ijspp.2018-0935.

[10] Seiler S, Haugen O, Kuffel E. Autonomic recovery after exercise in trained athletes: intensity and duration effects. Med Sci Sports Exerc 2007;39:1366–73. https://doi.org/10.1249/mss.0b013e318060f17d.

[11] Bishop DJ, Botella J, Granata C. CrossTalk opposing view: exercise training volume is more important than training intensity to promote increases in mitochondrial content. J Physiol 2019;597:4115–8. https://doi.org/10.1113/JP277634.

[12] Yan Z, Lira VA, Greene NP. Exercise training-induced regulation of mitochondrial quality. Exerc Sport Sci Rev 2012;40:159–64. https://doi.org/10.1097/JES.0b013e3182575599.

[13] Ventura-Clapier R, Garnier A, Veksler V. Transcriptional control of mitochondrial biogenesis: the central role of PGC-1. Cardiovasc Res 2008;79:208–17. https://doi.org/10.1093/cvr/cvn098.

[14] Coyle EF, Martin WH, Sinacore DR, Joyner MJ, Hagberg JM, Holloszy JO. Time course of loss of adaptations after stopping prolonged intense endurance training. J Appl Physiol 1984;57:1857–64. https://doi.org/10.1152/jappl.1984.57.6.1857.

[15] Daussin FN, Zoll J, Ponsot E, Dufour SP, Doutreleau S, Lonsdorfer E, Ventura-Clapier R, Mettauer B, Piquard F, Geny B, Richard R. Training at high exercise intensity promotes qualitative adaptations of mitochondrial function in human skeletal muscle. J Appl Physiol 2008;104:1436–41. https://doi.org/10.1152/japplphysiol.01135.2007.

[16] Tyler CM, Golland LC, Evans DL, Hodgson DR, Rose RJ. Skeletal muscle adaptations to prolonged training, overtraining and detraining in horses. Pflugers Arch Eur J Physiol 1998;436:391–7. https://doi.org/10.1007/s004240050648.

[17] Wong ASM, Morrice-West AV, Hitchens PL, Whitton RC. The association between thoroughbred racehorse training practices and musculoskeletal injuries in Victoria, Australia. Front Vet Sci 2023;10:1260554. https://doi.org/10.3389/fvets.2023.1260554.

[18] Tyler CM, Golland LC, Evans DL, Hodgson DR, Rose RJ. Changes in maximum oxygen uptake during prolonged training, overtraining, and detraining in horses. J Appl Physiol 1996;81:2244–9. https://doi.org/10.1152/jappl.1996.81.5.2244.

[19] Hamlin MJ, Shearman JP, Hopkins WG. Changes in physiological parameters in overtrained standardbred racehorses. Equine Vet J 2002;34:383–8. https://doi.org/10.2746/042516402776249146.

[20] Roy BA. Overreaching/overtraining: more is not always better, ACSM'S. Health Fit J 2015;19:4–5. https://doi.org/10.1249/FIT.0000000000000100.

[21] Bessa AL, Oliveira VN, Agostini GG, Oliveira RJS, Oliveira ACS, White GE, Wells GD, Teixeira DNS, Espindola FS. Exercise intensity and recovery: biomarkers of injury, inflammation, and oxidative stress. J Strength Cond Res 2016;30:311–9. https://doi.org/10.1519/JSC.0b013e31828f1ee9.

[22] Da Rocha AL, Pinto AP, Kohama EB, Pauli JR, De Moura LP, Cintra DE, Ropelle ER, Da Silva ASR. The proinflammatory effects of chronic excessive exercise. Cytokine 2019;119:57–61. https://doi.org/10.1016/j.cyto.2019.02.016.

[23] Thomson RL, Bellenger CR, Howe PRC, Karavirta L, Buckley JD. Improved heart rate recovery despite reduced exercise performance following heavy training: a within-subject analysis. J Sci Med Sport 2016;19:255–9. https://doi.org/10.1016/j.jsams.2015.02.010.

[24] Darr KC, Bassett DR, Morgan BJ, Thomas DP. Effects of age and training status on heart rate recovery after peak exercise. Am J Physiol-Heart Circ Physiol 1988;254:H340–3. https://doi.org/10.1152/ajpheart.1988.254.2.H340.

[25] Nobrega ACL, O'Leary D, Silva BM, Marongiu E, Piepoli MF, Crisafulli A. Neural regulation of cardiovascular response to exercise: role of Central command and peripheral afferents. BioMed Res Int 2014;2014:1–20. https://doi.org/10.1155/2014/478965.

[26] TYLER-McGOWAN CM, Golland LC, Evans DL, Hodgson DR, Rose RJ. Haematological and biochemical responses to training and overtraining. Equine Vet J 2010;31:621–5. https://doi.org/10.1111/j.2042-3306.1999.tb05297.x.

[27] Levy MN. Neural control of cardiac function. Baillieres Clin Neurol 1997;6:227–44.

[28] Rugh KS, Jiang B, Hatfield DG, Garner HE, Hahn AW. Mathematical modelling of post-exercise heart rate recovery in ponies. Biomed Sci Instrum 1992;28:151–6.

[29] Daanen HAM, Lamberts RP, Kallen VL, Jin A, Van Meeteren NLU. A systematic review on heart-rate recovery to monitor changes in training status in athletes. Int J Sports Physiol Perform 2012;7:251–60. https://doi.org/10.1123/ijspp.7.3.251.

[30] Gourine AV, Ackland GL. Cardiac vagus and exercise. Physiology 2019;34:71–80. https://doi.org/10.1152/physiol.00041.2018.

[31] Wilson G, McGowan CM. Recovery heart rates as a predictor of race position in race-fit National Hunt racehorses. CEP 2019;15:307–12. https://doi.org/10.3920/CEP180053.

[32] Yoshida T, Chida M, Ichioka M, Suda Y. Blood lactate parameters related to aerobic capacity and endurance performance. Eur J Appl Physiol 1987;56:7–11. https://doi.org/10.1007/BF00696368.

[33] Weltman A. The blood lactate response to exercise. Champaign, IL: Human Kinetics; 1995.

[34] Ghosh AK. Anaerobic threshold: its concept and role in endurance sport. Malays J Med Sci 2004;11:24–36.

[35] Evans DL, Harris RC, Snow DH. Correlation of racing performance with blood lactate and heart rate after exercise in thoroughbred horses. Equine Vet J 1993;25:441–5. https://doi.org/10.1111/j.2042-3306.1993.tb02987.x.

[36] Bitschnau C, Wiestner T, Trachsel DS, Auer JA, Weishaupt MA. Performance parameters and post exercise heart rate recovery in Warmblood sports horses of different performance levels: exercise testing in Warmblood sports horses. Equine Vet J 2010;42:17–22. https://doi.org/10.1111/j.2042-3306.2010.00260.x.

[37] Trilk JL, Lindner AJ, Greene HM, Alberghina D, Wickler SJ. A lactate-guided conditioning programme to improve endurance performance. Equine Vet J 2002;34:122–5. https://doi.org/10.1111/j.2042-3306.2002.tb05403.x.

[38] Kirsch K, Düe M, Holzhausen H, Sandersen C. Correlation of competition performance with heart rate and blood lactate response during interval training sessions in eventing horses. CEP 2019;15:187–98. https://doi.org/10.3920/cep180050.

[39] B. Kelemen, O. Benczenleitner, Laszlo Toth, Polarized and pyramidal training intensity distributions in distance running: an integrative literature review, (2024). https://doi.org/10.13140/RG.2.2.30810.11200.

[40] Campbell EH. Lactate-driven equine conditioning programmes. Vet J 2011;190:199–207. https://doi.org/10.1016/j.tvjl.2010.11.012.

[41] Fisher AL, Greene HM, Talmadge RJ, Nout-Lomas YS. Lactate-guided conditioning program using variable exercise intensities improves fitness and alters muscle enzyme activity but not inflammatory response in horses. CEP 2016;12:183–92. https://doi.org/10.3920/CEP160019.

[42] Santos MM, Benvenuto GV, Ramos GV, Titotto AC, Adão MDS, De Lacerda LDCC, Lisbôa JAN, Lacerda-Neto JCD. Effect of lactate minimum speed-guided conditioning on selected blood parameters of horses. J Equine Vet Sci 2022;119:104133. https://doi.org/10.1016/j.jevs.2022.104133.

[43] Ramos GV, Titotto AC, Costa GBD, Ferraz GDC, Lacerda-Neto JCD. Determination of speed and assessment of conditioning in horses submitted to a lactate minimum test—alternative approaches. Front Physiol 2024;15:1324038. https://doi.org/10.3389/fphys.2024.1324038.

[44] Czuba M, Zając A, Cholewa J, Poprzęcki S, Waśkiewicz Z, Mikołajec K. Lactate threshold (D-Max Method) and maximal Lactate steady State in cyclists. J Hum Kinet 2009;21:49–56. https://doi.org/10.2478/v10078-09-0006-5.

[45] Billat VL, Sirvent P, Py G, Koralsztein J-P, Mercier J. The concept of maximal lactate steady state: a bridge between biochemistry. Physiol Sport Sci 2003;33:407–26. https://doi.org/10.2165/00007256-200333060-00003. Sports Medicine.

[46] Gondim FJ, Zoppi CC, Pereira-da-Silva L, De Macedo DV. Determination of the anaerobic threshold and maximal lactate steady state speed in equines using the lactate minimum speed protocol. Comp Biochem Physiol A: Mol Integr Physiol 2007;146:375–80. https://doi.org/10.1016/j.cbpa.2006.11.002.

[47] De Maré L, Boshuizen B, Vidal Moreno De Vega C, De Meeûs C, Plancke L, Gansemans Y, Van Nieuwerburgh F, Deforce D, De Oliveira JE, Hosotani G, Oosterlinck M, Delesalle C. Profiling the aerobic window of horses in response to training by means of a modified lactate minimum speed test: flatten the curve. Front Physiol 2022;13:792052. https://doi.org/10.3389/fphys.2022.792052.

[48] Zhou S, Weston SB. Reliability of using the D -max method to define physiological responses to incremental exercise testing. Physiol Meas 1997;18:145–54. https://doi.org/10.1088/0967-3334/18/2/005.

[49] Titotto AC, Santos MM, Ramos GV, Adão MDS, Benvenuto GV, De Lacerda LCC, Lisbôa JAN, Lacerda-Neto JC. Effect of lactate minimum speed-guided training on the fluid, electrolyte and acid-base status of horses. Animals 2023;13:3290. https://doi.org/10.3390/ani13203290.