RESEARCH ARTICLE

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A Physiological Approach to Cardio-endurance Training: Indicators of Optimal Parasympathetic Input on Cardiovascular Regulation are Better Predictors of Running Performance of Distance Runners

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ABSTRACT

Poorly organized training schedules that are not focused on optimizing the cardiopulmonary fitness of the runner may lead to negative outcomes in their performance. Further, reduced cardiopulmonary fitness of a distance runner may lead to an imbalance of sympathetic and parasympathetic inputs of cardiac autonomic regulation. This altered balance of the regulation of the heart may recur as a vicious cycle, further hampering the runner's performance. The study assessed the effects of specialized training programs on the remodeling of cardiac autonomic regulation in relation to improving cardiopulmonary fitness and running performance of Sri Lankan male distance runners (N = 22). Before the intervention, runners were found to have more sympathetic dominancy on cardiac autonomic regulation along with suboptimal cardiopulmonary fitness level and suboptimal performance. After the intervention, more parasympathetic dominancy in cardiac autonomic regulation and improved cardiopulmonary fitness parameters were achieved. Post-intervention race timing of long-distance runners was significantly improved ($p < 0.05$) compared to the pre-intervention race timing irrespective of lower VO_{2peak} level. The specialized training program used in this study optimized the parasympathetic dominancy of the autonomic regulation of the cardiovascular system of the Sri Lankan national long-distance runners. The runners were able to record significantly improved race timing after the specialized training intervention even though their VO_{2peak} level was dropped. Thus, it is concluded that achieving parasympathetic dominant cardiac autonomic regulation is a better indicator than achieving higher VO_{2max} levels given the performance of distance runners.

Keywords: Cardiopulmonary fitness, cardiovascular regulation, performance.

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I. INTRODUCTION

A well-structured, scientific training schedule is the main requirement for long-distance runners to perform at their best in a running event. Adjustment and monitoring of planned training intensities by using physiological indicators is crucially important to enhance the performance of endurance athletes.

A. *Autonomic Regulation of Cardiovascular System of Distance Runners*

Critical adjustments to the cardiovascular system are continuously made to meet the demands of the skeletal muscles and the heart during exercises (Fagard, 1997; Makivić *et al.*, 2013; Vatner & Pagani, 1976). These dynamic cardiac and peripheral vascular control adjustments by higher centers and ANS result in rapid changes in heart rate, blood pressure, and the oscillation of perfusion demand of active muscles (Makivić *et al.*, 2013). Thus, cardiac autonomic regulation is modified in response to muscle contraction, the metabolic environment of the active muscles, and the oscillation of blood pressure during acute bouts of exercise (Bauer *et al.*, 1992).

The dynamic control of cardiac autonomic regulation is mainly determined by two mechanisms: the central command and the peripheral command (Mueller, 2010). Autonomic regulation via higher centers (central command) involving the arterial baroreceptors plays a key role in the cardiovascular adjustment during the exercise of a well-trained athlete. The rostral-ventero-lateral medulla (RVLM) of the brain stem receives a variety of afferent inputs from the active muscles (peripheral command) via metaboreceptors (type III afferents) and via mechanoreceptors (type IV afferents) during exercise

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(Mueller, 2010). The RVLM is the main relay point that decides the dominancy of the sympathetic or parasympathetic outflow to the heart and the vascular system. Further, exercise-related remodeling of cardiopulmonary baroreflex afferents at RVLM also controls the cardiac autonomic regulation during physical activity and rest (Fadel & Raven, 2012).

Endurance training promotes the baroreceptor activity and delays an individual's metaboreceptor activity and the mechanoreceptor activity (Fisher *et al.*, 2013). This altered peripheral command changes the summation of the afferent signals at the brain stem, resulting in reduced sympathetic outflow from the RVLM (Becker *et al.*, 2005; Sun *et al.*, 2012). The sympathetic and parasympathetic drives of the autonomic nervous system work reciprocally; an increase in the activity of one component causes or results from a decrease in the activity of the other (Levy, 1995). Thus, the decreased sympathetic excitatory tone results in increased parasympathetic inhibitory tone of cardiac autonomic regulation of a trained individual.

Long-term endurance training induces the parasympathetic nervous system (PNS) dominance of the autonomic control of sino-atrial node of the heart (Stein *et al.*, 2002). This shift of the sympatho-vagal balance causes sinus bradycardia in resting conditions and a slower increase in heart rate at any degree of submaximal oxygen uptake during intense physical activity (Uusitalo *et al.*, 1996, 2000). Facioli *et al.* (2021) elaborated in their study that the parasympathetic dominancy of ANS causes better heart rate recovery (HRR) in well-trained athletes. Poorly programmed training schedules that are not targeted to improve CVS fitness may drive the athletes to a physically stressed condition that leads to an unhealthy, sympathetic, overactive state (Coates *et al.*, 2018). That will show a high LF/HF ratio level in HRV assessments.

B. Heart Rate Variability (HRV)

Heart rate variability (HRV) is the fluctuation of the time intervals between adjacent heartbeats (McCraty & Shaffer, 2015). HRV indicates neuroendocrine coordination and is generated by heart-brain interaction and dynamic non-linear autonomic nervous system processes (Shaffer & Ginsberg, 2017). More precisely, HRV reflects the regulation of autonomic balance, cardiac functions, blood pressure, gas exchange, and vascular tone of an individual (Gevirtz & Lehrer, 2016). HRV is a better tool for quantitative assessment of autonomic control of the heart in different physiological conditions at rest and during physical activity (Malik *et al.*, 1996). The HRV indices may change according to the intensity, duration, and type of training (O'Sullivan & Bell, 2000).

In the literature, researchers used short-term (5-minute) HRV testing using frequency domain measurements to assess the low-frequency (LF) band and the high-frequency (HF) band (Michael *et al.*, 2017; Shaffer & Ginsberg, 2017). The LF band (0.04–0.15Hz) is influenced by the activity of both the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS) (Shaffer & Ginsberg, 2017; Shaffer *et al.*, 2014). HF band (respiratory band; 0.15–0.40 Hz) is influenced only by PNS (Malik *et al.*, 1996). The LF/HF ratio reflects the ratio between the activity of SNS and PNS under controlled conditions (Shaffer *et al.*, 2014). The low LF/HF ratio indicates the PNS dominancy on cardiac regulation (Shaffer & Ginsberg, 2017).

C. Cardio-pulmonary Exercise Fitness Testing (CPET)

CPET parameters such as peak oxygen consumption ($VO2_{peak}$), anaerobic threshold (AT), serum lactic acid level in rest (LA_{rest}), serum lactic acid level in peak exercise (LA_{peak}), resting heart rate (HR_{rest}), peak heart rate (HR_{peak}) and heart rate recovery (HRR) reflect the integrated ability to transport oxygen from the atmosphere to the mitochondria to perform physical work and the ability of recovery of the cardiopulmonary systems. It, therefore, more elaborately defines the functional capacity of an individual. Thus, CPET parameters are dependent on a linked chain of processes that include pulmonary ventilation and diffusion, cardiac autonomic control, functions of the right and left ventricles (during both systole and diastole), the ability of the vasculature to accommodate and efficiently transport blood from the heart to active muscles and the ability of the muscle cells to receive and use the oxygen and nutrients delivered by the blood (Ross *et al.*, 2016).

The most important factors that influence the individual differences in $VO2_{peak}$ are exercise mode and the person’s training state, heredity, gender, body composition, and chronological age. $VO2_{peak}$ is the most popular CPET parameter amongst trainers and is the gold standard monitoring tool in most training programs (Gordon *et al.*, 2011; Hottenrott *et al.*, 2012).

D. Objectives of the Study

The study was planned to assess the effects of a specialized endurance training program on the remodeling of cardiac autonomic regulation by using HRV, cardiopulmonary fitness level by using CPET parameters ($VO2_{peak}$, AT, LA_{rest}, LA_{peak}, HR_{rest}, HR_{peak}, and HRR), and running performance measured by race timing, exercise duration and a peak workload of Sri Lankan, national-level male long-distance runners.

II. METHODOLOGY

An interventional study was conducted at the Department of Physiology, Faculty of Medical Sciences, University of Sri Jayewardenepura, Sri Lanka. Ethical clearance for the study was obtained from the ethical review committee (ERC) of the Faculty of Medical Sciences, University of Sri Jayewardenepura, Sri Lanka.

In this study, 22 Sri Lankan national-level male long-distance runners were assessed. The runners' anthropometry (height, weight, body mass index-BMI) was assessed by standard measures. The CPET parameters (VO_{2peak}, AT, LA_{rest}, LA_{peak}, HR_{rest}, $HR_{peak,}$ and HRR), race timing, exercise duration on a cycle ergometer, and peak workload were assessed before and after the training intervention.

A. HRV Assessment

The runner was asked to sit comfortably on a chair and rest for 15 minutes before the test was done. Limb-led ECG electrodes and respiratory belt were attached to the runner, and they were instructed to maintain a forced grip of the right hand around 30 Newton on the hand dynamometer for 05 minutes. The heart rate variability monitor (PowerLab-26T^{TM}, $AD_{instruments}$, New Zealand) automatically recorded the R-R interval and produced results. The width of the low frequency (LF) band representing the sympathetic tone, the width of the high frequency (HF) band representing the parasympathetic tone, and the LF/HF ratio were assessed.

B. CPET Assessment

CPET parameters (VO_{2max}, AT, HR_{rest}, HR_{peak}, HRR, peak workload, exercise duration) were assessed with an automated cardiopulmonary exercise testing machine and cycle ergometer (Fitmate^{TM}, Cosmed, Rome, Italy) by using incremental ramp protocol. CPET assessments were done in the morning hours to prevent diurnal variation.

LA_{rest} and LA_{peak} were measured with a finger prick sample of blood by using an automated lactic acid analyzer (Lactate plus^{TM}, Nova Biomedical, Waltham, MA, USA). A body composition analyzer (Tanita^{TM}, Tokyo, Japan) was used to assess the body fat percentage of long-distance runners before and after the training intervention.

C. Specialized Training Program

A 12-week-long specialized training program was planned according to the runners' initial race timing, HRV parameters, and CPET parameters. The training was carried out at an altitude of 4,918 feet in Diyathalawa and Bandarawela, Sri Lanka. High-altitude training could not be implemented due to geographical and logistic limitations.

The physical training period was divided into two parts: (1) The preparatory period (first 4 weeks) with low-intensity training and (2) the period of progressively increasing training intensity (8 weeks). The first 4 weeks were divided into 4 training micro cycles with 7 days per cycle, and the second 8 weeks were divided into 06 training micro cycles with 10 days per cycle.

Training intensities for each runner were set up using target heart rates (THR; Hydren & Cohen, 2015; Wijayasiri *et al.*, 2018). The training program consisted of about 80% of the total running time on long-duration slow, continuous runs at the heart rate of AT of individual runners. 20% of total training time was allocated for high-intensity running at a heart rate above 70% of VO_{2max} with active rest intervals (high-intensity interval training). For the first time in Sri Lankan training literature, supervised breathing exercises and supervised active rest during the training sessions were introduced to the training program. The sleeping habits of the runners were closely supervised, allowing them to have more than 7 hours of good-quality sleep during the night.

Strength training was introduced, targeting the core muscles and leg muscles to improve the speed and tolerance of the runners.

Nutrition intervention was planned mainly targeting correction of body fat percentage into the ideal range (6–8% of body weight) for a long-distance runner (Fleck, 1983). Daily hydration and electrolyte supplements were enhanced with water, electrolyte drinks (oral rehydration fluid), and fruit juice.

D. Assessment of the Athletes

All the parameters assessed (anthropometry, HRV, VO_{2peak}, AT, LA_{rest}, LA_{peak}, HR_{rest}, HR_{peak}, and HRR) in the initial assessment of the runners were repeated after the 12 weeks of specialized training intervention to assess the effect of the training program.

The performances of the long-distance runners were assessed by comparing their best race timing of a 10,000m competitive running event, exercise duration on a cycle ergometer, and peak workload before and after the intervention.

Data were analyzed using SPSS v.16. The paired t-test was used to analyze the pre-intervention and post-intervention data. Significance was set at a p-value less than 0.05 with a 95% confidence interval.

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III. RESULTS

Table I indicates the anthropometry parameters of the long-distance runners. As expected, the weight and BMI of long-distance runners were not significantly changed during the 12-week-long training intervention ($p > 0.05$).

TABLE I: ANTHROPOMETRY MEASUREMENTS OF NATIONAL-LEVEL LONG-DISTANCE RUNNERS BEFORE AND AFTER THE SPECIALIZED TRAINING

	Pre-intervention (N = 22) Mean ± SD	Post-intervention (N = 22) Mean ± SD	p-value
Height (cm)	1.67 ± 5.9	1.67 ± 6.1	0.780
Weight (kg)	53.2 ± 4.4	53.0 ± 4.3	0.773
BMI	19.0 ± 1.1	18.9 ± 1.0	0.780

As depicted in Table II, endurance training hours were increased more than 3 times, and the training time of strength training of core muscles was increased more than 5 times during the training intervention. Breathing exercises were introduced newly into the training program. Resting hours were increased and supervised to match the training program best.

TABLE II: THE TRAINING INTERVENTION

	Pre-intervention (N = 22) Mean ± SD	During intervention (N = 22) Mean ± SD
Endurance training (hrs/week)	5.78 ± 2.44	17.27 ± 6.5
Speed training (hours/week)	2.75 ± 2.65	No speed training
Strength training (hours/week)	0.49 ± 0.63	2.28 ± 0.19
Breathing training (hours/week) Respiratory muscle endurance training (RMET)	No breathing exercises	8.00
Rest (hours/ week)	About 40 hours per week; no special organized rest time included in the training	Per week = 100+ hours 2nd, 4th, 6th, 9th day evening rest 10th full day rest (10 days mesocycle). During the rest, runners practiced breathing training.

Table III summarizes the HRV data of long-distance runners in pre-intervention and post-intervention assessment. The LF band (representing the sympathetic tone) was significantly reduced, and the HF band (representing the parasympathetic tone) was significantly increased after the intervention program. This change significantly reduced the LF/HF ratio, highlighting the dominant parasympathetic tone on cardiac regulation of long-distance runners.

TABLE III: HEART RATE VARIABILITY OF RUNNERS

	Pre-intervention (N = 22) Mean ± SD	Post-intervention (N = 22) Mean ± SD	p-value
LF (nu)	48.83 ± 16.60	38.73 ± 14.13	0.007
HF (nu)	45.96 ± 14.83	56.57 ± 13.31	0.003
LF/HF ratio	1.37 ± 1.14	0.76 ± 0.42	0.018

Table IV shows the CPET parameters of the long-distance runners before and after the training intervention. Even though VO_{2max} showed a significant decline ($p < 0.05$) in the post-intervention assessment, it was maintained above 60 ml-1.Kg-1.min-1. The AT and mean LA_{rest} and LA_{peak} were significantly improved ($p < 0.05$) in the post-intervention assessment than in the pre-intervention assessment of the long-distance runners.

TABLE IV: CARDIOPULMONARY EXERCISE FITNESS TESTING DATA OF LONG-DISTANCE RUNNERS

Pre-intervention (N = 18) Mean ± SD	Post-intervention (N = 18) Mean ± SD	p-value
VO_{2max} (ml.Kg^{-1}.min^{-1})	66.34 ± 2.8	61.63 ± 4.7
AT (%)	39.44 ± 4.8	46.61 ± 6.1
AT_{VO2} (ml.Kg^{-1}.min^{-1})	26.17 ± 3.7	28.78 ± 4.2
LA_{rest} (mmol. L^{-1})	5.36 ± 3.1	1.81 ± 0.64
LA_{peak} (mmol. L^{-1})	13.73 ± 4.0	9.37 ± 1.7
Peak Work load (W)	311.11 ± 22.8	349.78 ± 35.8

Table V summarizes the heart rate dynamics data of the long-distance runners before and after the training intervention. HR_{rest}, $HR_{peak,}$ and HRR were assessed during the CPET in laboratory settings. No significant difference in post-intervention HR_{peak} was observed even though the exercise duration and the peak workload were significantly improved (Table VI) compared to the pre-intervention assessment. HRR (beats per minute and percentage of reduction) at 90 seconds and 3 minutes after the submaximal exercise on the cycle ergometer were significantly increased in the post-intervention assessment than in the pre-intervention assessment.

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TABLE V: RESTING HEART RATE, PEAK HEART RATE, AND HEART RATE RECOVERY OF LONG-DISTANCE RUNNERS

	Pre-intervention (N = 18) Mean ± SD	Post-intervention (N = 18) Mean ± SD	p-value
	VO_{2max} (ml.Kg^{-1}.min^{-1})	66.34 ± 2.8	61.63 ± 4.7
	AT (%)	39.44 ± 4.8	46.61 ± 6.1
	AT_{VO2} (ml.Kg^{-1}.min^{-1})	26.17 ± 3.7	28.78 ± 4.2
	LA_{rest} (mmol. L^{-1})	5.36 ± 3.1	1.81 ± 0.64
	LA_{peak} (mmol. L^{-1})	13.73 ± 4.0	9.37 ± 1.7
	Peak Work load (W)	311.11 ± 22.8	349.78 ± 35.8

The mean race timing of the 10,000m running event of the long-distance runners was significantly improved after the training intervention ($p < 0.05$; see Table VI). This improvement in timing was further corroborated by the significantly increased exercise duration ($p < 0.05$) and peak workload ($p < 0.05$) on CPET on the cycle ergometer post-intervention (see Table IV and Table VI).

TABLE VI: RACE TIMING AND EXERCISE DURATION OF LONG-DISTANCE RUNNERS

	Pre-intervention (N = 18) Mean ± SD	Post-intervention (N = 18) Mean ± SD	p-value
Exercise duration (minutes)	12.88 ± 0.76	13.92 ± 1.2	0.004
Race timing (minutes)	34.23 ± 1.3	33.12 ± 1.3	0.001

IV. DISCUSSION

This study assessed the effect of the remodeling of cardiac autonomic regulation on running performance and cardiopulmonary fitness parameters of male national long-distance runners before and after a specialized training intervention program of 12 weeks duration. The results showed significant improvement of the parasympathetic dominancy on cardiac autonomic regulation, resulting in better running performance of long-distance runners irrespective of the changes in the VO_{2peak} level.

To the best of the author's knowledge, this is the first and only study conducted in Sri Lanka to assess the effect of specialized training on cardiac autonomic regulation, cardiopulmonary functions, and athletes' sports performance.

The human body initially reacts to physical exercise by decreasing vagal tone, followed by sympathetic activation of ANS (Raczak *et al.*, 2006). Therefore, a high vagal tone is beneficial for a long-distance runner as it will lengthen the withdrawal time of the vagal tone and delay the activation of the sympathetic drive during continuous physical exercise. Thus, training programs for long-distance runners should be focused on achieving higher vagal tone in cardiac autonomic regulation of the runners to improve performance and race timing. Further, this remodeling will improve the recovery of the cardiovascular system of the long-distance runners, hence promoting additional health benefits, too.

The specialized physical training intervention in the present study was planned according to the pre-intervention HRV data and CPET parameters of national male long-distance runners. During the intervention, the number of hours of aerobic endurance training was increased by about 3 times (Table II). Speed training was removed entirely from the training program in the first half of the intervention. Core muscle strengthening exercises were newly introduced in addition to the lower limb muscle strengthening exercises. The time allocation for strengthening exercises was increased from 0.49 ± 0.63 hours per week (pre-intervention) to 2.28 ± 0.19 hours per week during the intervention. For the first time in Sri Lanka, respiratory muscle endurance training (RMET) was introduced in the training program of long-distance runners. An average of 8 hours per week was allocated for RMET, targeting mainly the diaphragm and the other respiratory muscles. These RMET exercises and core muscle strength training were practiced for better results. Further, the runners were encouraged to continue RMET exercises during the recovery period without disturbing the routine of daily activity.

The recovery process in sports is essential in determining subsequent athletic performance (Monedero & Donne, 2000). The recovery program was rescheduled and tightly supervised by the relevant coaches in the present study. As explained in the literature, active recovery was the most effective intervention to remove serum LA at minutes 9 and 12 in the post-exercise period (Ahmaidi *et al.*, 1996; Monedero & Donne, 2000). Many researchers have explained that intermittent interval training with an activity-recovery ratio around 1:0.5 and 1:1 improves endurance capacity (Arbab-Zadeh *et al.*, 2014; McArdle *et al.*, 2016). Therefore, active recovery interventions were planned as intermittent interval training in 1:0.5 and 1:1 activity-recovery ratios.

Burges *et al.* (1997) described that the sympathetic nervous system activity is decreased with uninterrupted high-quality sleep of longer sleep duration. Therefore, the runners were encouraged to have good quality continuous sleep at night. This supervised sleep intervention was part of the specialized training program to ensure complete mental and physical recovery. This intervention modality was in accordance with recent studies done on sleeping patterns and the performance of athletes (Covassin *et al.*, 2013; Roberts *et al.*, 2019).

The results of the post-intervention assessment showed that the newly adopted training intervention remodeled the runners' cardiac autonomic regulation into a state of dominant parasympathetic tone over sympathetic tone. This is confirmed by the finding of the post-intervention LF/HF ratio of the HRV assessment. The LF band (sympathetic tone) was significantly decreased compared to the pre-intervention level ($p < 0.05$). In contrast, the post-intervention HF band (parasympathetic tone) was significantly increased than the pre-intervention level ($p < 0.05$). The post-intervention average LF/HF ratio was also significantly reduced than that of the pre-intervention level ($p < 0.05$), highlighting the dominant parasympathetic activity over the sympathetic activity of ANS regulation of the cardiovascular system amongst the runners. Further to HRV changes, lower levels of post-intervention serum lactic acid levels and late onset of AT (Table IV) indicate the relatively higher contribution of the aerobic energy system during the activity. Improved metabolic response at the muscle level had significantly reduced the over-activity of the metabo-reflex, which was clearly observed by improved HRV parameters. This finding is in accordance with the findings of the previous studies (Stanley *et al.*, 2013).

A. Effects of Training Intervention on HRR

Like the feedforward and feedback regulation of many systems in the body during exercise, post-exercise recovery is also regulated by complex neuro-cardiogenic (Peçanha *et al.*, 2014; Stanley *et al.*, 2013). Post-exercise HRR consists of an initial decay mainly determined by parasympathetic reactivation followed by a decay that is attributed to a sum of parasympathetic reactivation and sympathetic withdrawal (Imai *et al.*, 1994).

As elaborated by the results of this study, progressive removal of metabolites from the muscles during the post-exercise period would gradually diminish the metabo-reflex activation, leading to a progressive restoration of baro-reflex activity, which could then contribute to increased parasympathetic and decreased sympathetic activity to the heart. This could result in a progressive decrease in HR during the recovery after exercise (Fisher *et al.*, 2013; Hartwich *et al.*, 2011; Peçanha *et al.*, 2014). As highlighted by the study results, post-intervention HRR at 90 seconds and 3 minutes after Sri Lankan long-distance runners exercise significantly improved than the pre-intervention HRR at 90 seconds and 3 minutes after exercise. HRR at around 60 to 90 seconds after the exercise can be taken as the marker of parasympathetic reactivation responsible for the initial drop in the heart rate. HRR around 3 to 5 minutes after exercise can be taken as the marker of the sum of parasympathetic reactivation and sympathetic withdrawal responsible for heart rate decay (Peçanha *et al.*, 2014). Therefore, the newly imposed training intervention for long-distance runners positively affected the improvement of both parasympathetic reactivation responsible for initial recovery of the heart and the withdrawal of sympathetic over-activity in later recovery of the heart.

B. Effect of Training Intervention on AT and LA Levels

At the pre-intervention assessment, long-distance runners had early onset AT at lower VO_2 levels and very high LA_{rest} and LA_{peak} levels (Table IV). Speed training employed arbitrarily in traditional training programs has contributed to the pre-intervention results.

As shown by the results, the LA_{rest} and LA_{peak} were significantly decreased in the post-training assessment compared to the pre-training levels of the runners. The reductions in serum LA levels were further supported by the significant improvement of the AT and AT_{VO2} of the runners (Table IV).

Poor blood supply to active muscles during and after exercise leads to "perfusion- demand mismatch" and accumulation of metabolites. Post-exercise HRR is significantly depressed in healthy individuals having higher exercise-induced serum LA levels (Ba *et al.*, 2009). A similar relationship was observed in the pre-intervention assessment of long-distance runners. A high mean LA_{peak} level was found, along with a higher LF/HF ratio and suboptimal HRR at 90 seconds and at 3 minutes. Based on the pre-intervention results, it can be concluded that increased metabo-reflex activity and reduced baro-reflex sensitivity due to higher serum LA levels sustained the higher sympathetic tone on cardiac autonomic regulation during the post-exercise period of Sri Lankan long-distance runners. Higher metabo-reflex activity causing higher sympathetic tone is the main reason for diminished post-exercise HRR kinetics of Sri Lankan long-distance runners. After the training intervention, the LA_{peak} level was significantly reduced along with the lower LF/HF ratio and improved HRR at 90 seconds and 3 minutes after exercise. Compared to pre-intervention results, the significantly reduced LA_{peak} levels in the athletes after the training intervention emphasized the reduction in the metabo-reflex activity, increasing the sensitivity of the baroreflex tone on the regulation of the heart during the recovery period.

C. Maximum Oxygen Consumption (VO_{2max})

Cardiopulmonary efficiency refers to optimal oxygen transport and utilization during an intense endurance physical activity such as long-distance running (Barnes & Kilding, 2015). This further reinforces that highly economical runners will achieve higher running speed at the same VO_{2max} level compared to less economical runners. In the present study, even though the post-intervention mean

VO_{2max} of long-distance runners was significantly lower than the pre-intervention mean VO_{2max}, post-intervention mean race timing, post-intervention exercise duration on a cycle ergometer and peak workload were significantly improved compared to pre-intervention race timing ($p < 0.05$) with comparatively low O_2 consumption after the specialized training intervention. The higher performance with lower O_2 consumption obtained after the specialized training intervention indicates the significant improvement in the running economy achieved by the Sri Lankan long-distance runners. Since the exercise duration and peak workload on the cycle ergometer were increased along with significantly improved race timing, it is unlikely that motivational factors would have influenced the test results.

V. Conclusion

Despite the higher VO_{2max} level, poorly organized training schedules led to sympathetic dominance of cardiac autonomic regulatory mechanisms of Sri Lankan long-distance runners. This results in suboptimal remodeling of serum lactic acid levels, HRR, and cardiopulmonary fitness, tarnishing the optimal performance of Sri Lankan long-distance runners.

To the best of the author's knowledge, this is the first study that assessed the CPET parameters, HRV parameters, race timings, and performance amongst Sri Lankan long-distance runners. Further, for the first time in Sri Lanka, correct combinations of different training modalities (running at THR, RMET, cross training, and core muscle strength training) were adopted into the training programs of long-distance runners.

Training schedules targeted to enhance the parasympathetic tone on cardiac autonomic regulation and optimal cardiac remodeling are essential to improve the lactate profile and cardiopulmonary fitness parameters amongst Sri Lankan long-distance runners. The training methods used in this study successfully achieved increased parasympathetic tone on cardiac autonomic regulation as indicated by a lower LF band, Higher HF band, and lower LF/HF ratio. Further, the training modalities successfully achieved better remodeling of CPET parameters. Optimal remodeling of cardiac autonomic regulation in a parasympathetic dominant state associated with ideal CPET parameters had resulted in better race timings and performance amongst Sri Lankan long-distance runners.

In conclusion, optimal remodeling of the HRV parameters of cardiac autonomic regulation into a parasympathetic dominant state and other CPET parameters can be taken as better indicators of running performance than achieving only higher VO_{2max} levels amongst long-distance runners.

VI. Recommendations

Training schedules of long-distance runners must be focused on improving the key physiological parameters such as functional modifications of cardiac autonomic regulation, modification of the lactate profile, and maintaining an adequate VO_{2max} level. Further, the training programs for long-distance runners should implement periodical monitoring of improvement of physiological factors by using HRV assessment, lactate profile, and other CPET parameters.

Setting up the running intensities for long-distance runners should be based on THR instead of running time. Breathing exercises should be practiced and incorporated into the training programs of long-distance runners. Closely supervised recovery intervention should also be adopted in the training programs of long-distance runners.

Finally, the knowledge and attitudes of coaches regarding the physiological training and monitoring of long-distance runners and the newest training guidelines must be enhanced.

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CONFLICT OF INTEREST

The authors report there are no competing interests to declare.

REFERENCES

Ahmaidi, S., Granier, P., Taoutaou, Z., Mercier, J., Dubouchaud, H., & Prefaut, C. (1996). Effects of active recovery on plasma lactate and anaerobic power following repeated intensive exercise. *Medicine and Science in Sports and Exercise, 28,* 450–456.

Arbab-Zadeh, A., Perhonen, M., Howden, E., Peshock, R. M., Zhang, R., Adams-Huet, B., Haykowsky, M. J., & Levine, B. D. (2014). Cardiac remodeling in response to 1 year of intensive endurance training. *Circulation, 130,* 2152–2161.

Ba, A., Delliaux, S., Bregeon, F., Levy, S., & Jammes, Y. (2009). Post-exercise heart rate recovery in healthy, obeses, and COPD subjects: Relationships with blood lactic acid and PaO2 levels. *Clinical Research in Cardiology, 98,* 52–58.

Barnes, K. R., & Kilding, A. E. (2015). Running economy: measurement, norms, and determining factors. *Sports Medicine-Open, 1*(1), 1–15.

Bauer, R., Waldrop, T., Iwamoto, G., & Holzwarth, M. (1992). Properties of ventrolateral medullary neurons that respond to muscular contraction. *Brain Research Bulletin, 28,* 167–178.

Becker, L. K., Santos, R. A., & Campagnole-Santos, M. J. (2005). Cardiovascular effects of angiotensin II and angiotensin-(1–7) at the RVLM of trained normotensive rats. *Brain Research*, *1040,* 121–128.

Burgess, H. J., Trinder, J., Kim, Y., & Luke, D. (1997). Sleep and circadian influences on cardiac autonomic nervous system activity. *American Journal of Physiology-Heart and Circulatory Physiology*, *273*(4), H1761–H1768.

Coates, A. M., Millar, P. J., & Burr, J. F. (2018). Blunted cardiac output from overtraining is related to increased arterial stiffness. *Medicine & Science in Sports & Exercise*, *50*(12), 2459–2464.

Covassin, N., De Zambotti, M., Cellini, N., Sarlo, M., & Stegagno, L. (2013). Cardiovascular down-regulation in essential hypotension: Relationships with autonomic control and sleep. *Psychophysiology, 50,* 767–776.

Facioli, T. P., Philbois, S. V., Gastaldi, A. C., Almeida, D. S., Maida, K. D., Rodrigues, J. A., Sánchez-Delgado, J. C., & Souza, H. C. (2021). Study of heart rate recovery and cardiovascular autonomic modulation in healthy participants after submaximal exercise. *Scientific Reports*, *11*(1), 1–9.

Fadel, P. J., & Raven, P. B. (2012). Human investigations into the arterial and cardiopulmonary baroreflexes during exercise. *Experimental Physiology, 97,* 39–50.

Fagard, R. H. (1997). Impact of different sports and training on cardiac structure and function. *Cardiology Clinics, 15*(3), 397–412.

Fisher, J. P., Adlan, A. M., Shantsila, A., Secher, J. F., Sorensen, H., & Secher, N. H. (2013). Muscle metaboreflex and autonomic regulation of heart rate in humans. *The Journal of Physiology*, *591*(15), 3777–3788.

Fleck, S. J. (1983). Body composition of elite American athletes. *The American Journal of Sports Medicine*, *11*(6), 398–403.

Gevirtz, R. N., & Lehrer, P. M. (2016). Cardiorespiratory biofeedback. In M. Schwartz & F. Andrasik (Eds.), *Biofeedback: A practitioner's guide (*4th ed.). The Guilford Press.

Gordon, D., Hopkins, S., King, C., Keiller, D., & Barnes, R. J. (2011). Incidence of the plateau at VO2max is dependent on the anaerobic capacity. *International Journal of Sports Medicine, 32*(1), 1–6.

Hartwich, D., Dear, W. E., Waterfall, J. L., & Fisher, J. P. (2011). Effect of muscle metaboreflex activation on spontaneous cardiac baroreflex sensitivity during exercise in humans. *The Journal of Physiology*, *589*(24), 6157–6171.

Hottenrott, K., Ludyga, S., & Schulze, S. (2012). Effects of high intensity training and continuous endurance training on aerobic capacity and body composition in recreationally active runners. *Journal of Sports Science & Medicine, 11*(3), 483–488.

Hydren, J. R., & Cohen, B. S. (2015). Current scientific evidence for a polarized cardiovascular endurance training model. *The Journal of Strength & Conditioning Research*, *29*(12), 3523–3530.

Imai, K., Sato, H., Hori, M., Kusuoka, H., Ozaki, H., Yokoyama, H., Takeda, H., Inoue, M., & Kamada, T. (1994). Vagally mediated heart rate recovery after exercise is accelerated in athletes but blunted in patients with chronic heart failure. *Journal of the American College of Cardiology, 24,* 1529–1535.

Levy, M. N. (1995). Neural control of the heart: The importance of being ignorant. *Journal of Cardiovascular Electrophysiology*, *6*(4), 283–293.

Makivić, B., Nikić Djordjević, M., & Willis, M. S. (2013). Heart Rate Variability (HRV) as a tool for diagnostic and monitoring performance in sport and physical activities. *Journal of Exercise Physiology Online, 16*(3), 103–131.

Malik, M., Bigger, J. T., Camm, A. J., Kleiger, R. E., Malliani, A., Moss, A. J., & Schwartz, P. J. (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *European Heart Journal*, *17*(3), 354-381.

McArdle, W. D., Katch, F. I., & Katch, V. L. (2016). Training the anaerobic and aerobic energy systems. In W. D. McArdle, F. I. Katch & V. L. Katch (Eds.). *Essentials of exercise physiology (*5th ed.). Philadelphia: Wolters Kluwer.

McCraty, R., & Shaffer, F. (2015). Heart rate variability: New perspectives on physiological mechanisms, assessment of self-regulatory capacity, and health risk. *Global Advances in Health and Medicine*, *4*(1), 46–61.

Michael, S., Graham, K. S., & Davis, G. M. (2017). Cardiac autonomic responses during exercise and post-exercise recovery using heart rate variability and systolic time intervals—A review. *Frontiers in Physiology, 8,* 1–19.

Monedero, J., & Donne, B. (2000). Effect of recovery interventions on lactate removal and subsequent performance. *International Journal of Sports Medicine*, *21*(08), 593–597.

Mueller, P. J. (2010). Physical (in)activity-dependent alterations at the rostral ventrolateral medulla: influence on sympathetic nervous system regulation. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *298*(6), R1468–R1474.

O'Sullivan, S. E., & Bell, C. (2000). The effects of exercise and training on human cardiovascular reflex control. *Journal of the Autonomic Nervous System*, *81*(1-3), 16–24.

Peçanha, T., Silva-Júnior, N. D., & Forjaz, C. L. de M. (2014). Heart rate recovery: autonomic determinants, methods of assessment and association with mortality and cardiovascular diseases. *Clinical Physiology and Functional Imaging, 34*(5), 327-339.

Raczak, G., Danilowicz-Szymanowicz, L., Kobuszewska-Chwirot, M., Ratkowski, W., Figura-Chmielewska, M., & Szwoch, M. (2006). Long-term exercise training improves autonomic nervous system profile in professional runners. *Kardiologia Polska (Polish Heart Journal)*, *64*(2), 135–140.

Roberts, S. S., Teo, W.-P., Aisbett, B., & Warmington, S. A. (2019). Extended sleep maintains endurance performance better than normal or restricted sleep. *Medicine and Science in Sports and Exercise, 51,* 2516–2523.

Ross, R., Blair, S. N., Arena, R., Church, T. S., Després, J.-P., Franklin, B. A., Haskell, W. L., Kaminsky, L. A., Levine, B. D., Lavie, C. J., Myers, J., Niebauer, J., Sallis, R., Sawada, S. S., Sui, X., & Wisløff, U. (2016). Importance of assessing cardiorespiratory fitness in clinical practice: A case for fitness as a clinical vital sign: A scientific statement from the American Heart Association. *Circulation, 134*(24), e653-e699.

Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in Public Health, 5,* 1–17.

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Shaffer, F., McCraty, R., & Zerr, C. L. (2014). A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability. *Frontiers in Psychology, 5,* 1–19.

Stanley, J., Peake, J. M., & Buchheit, M. (2013). Cardiac parasympathetic reactivation following exercise: Implications for training prescription. *Sports Medicine, 43,* 1259–1277.

Stein, R., Medeiros, C. M., Rosito, G. A., Zimerman, L. I., & Ribeiro, J. P. (2002). Intrinsic sinus and atrioventricular node electrophysiologic adaptations in endurance athletes. *Journal of the American College of Cardiology*, *39*(6), 1033–1038.

Sun, H.-J., Li, P., Chen, W.-W., Xiong, X.-Q., & Han, Y. (2012). Angiotensin II and angiotensin-(1-7) in paraventricular nucleus modulate cardiac sympathetic afferent reflex in renovascular hypertensive rats. *PLoS One, 7,* 1–11.

Uusitalo, A. L. T., Tahvanainen, K. U. O., Uusitalo, A. J., & Rusko, H. K. (1996). Non-invasive evaluation of sympathovagal balance in athletes by time and frequency domain analyses of heart rate and blood pressure variability. *Clinical Physiology, 16*(6), 575–588.

Uusitalo, A. L. T., Uusitalo, A. J., & Rusko, H. K. (2000). Heart rate and blood pressure variability during heavy training and overtraining in the female athlete. *International Journal of Sports Medicine*, *21*(01), 45–53.

Vatner, S. F., & Pagani, M. (1976). Cardiovascular adjustments to exercise: hemodynamics and mechanisms. *Progress in Cardiovascular Diseases, 19*(2), 91–108.

Wijayasiri, K. D. C. U., Wimalasekera, S. W., Waidyasekara, H., Sivayogan, S., & Thurairaja, C. (2018). Effectiveness of training on cardiopulmonary fitness of Sri Lankan national sprinters. *The Ceylon Medical Journal*, *63*(01), 39.