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Universidad del País Vasco

Euskal Herriko Unibertsitatea

International Doctorate

A NOVEL APPROACH TO TRAINING ANALYSIS FOR DISTANCE RUNNERS BASED ON RACE-PACE

Mark Kenneally

Supervisors:

Jordan Santos-Concejero & Arturo Casado Alda

Vitoria-Gasteiz, 2022

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Arturo Casado Alda

Universidad Rey Juan Carlos

Vitoria-Gasteiz, 2022

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Doktorego programa / Programa de doctorado: Actividad Física y Deporte

Doktoregaiaren izen-abizenak / Nombre y apellidos del/la doctorando/a: Mark Kenneally

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Tokia eta data / Lugar y fecha: Vitoria-Gasteiz, 19 de Mayo de 2022

Sin. / Fdo.: Tesiaren zuzendariak / los directores de la tesis

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DEPARTMENT AUTHORISATION

The Board of the Department PHYSICAL EDUCATION AND SPOR, during its meeting held on 17th of June, 2022 agreed to authorise the processing of the Doctoral Thesis entitled: "**A NOVEL APPROACH TO TRAINING ANALYSIS FOR DISTANCE RUNNERS BASED ON RACE-PACE"**, supervised by **Dr. JORDAN SANTOS CONCEJERO** and **Dr. ARTURO CASADO ALDA**, and presented by **Mr. MARK KENNEALLY** to this Department.

In Vitoria-Gasteiz, on 17 of June, 2022

THE DEPARTMENT DIRECTOR   DEPARTMENT SECRETARY

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AUTHORISATION OF THE DOCTORAL PROGRAMME'S ACADEMIC COMMISSION

The Academic Commission of the Doctoral Programme in PHYSICAL ACTIVITY AND SPORT during its meeting held on __of June, 2022, agreed to authorise the presentation of the Doctoral Thesis entitled: "**A NOVEL APPROACH TO TRAINING ANALYSIS FOR DISTANCE RUNNERS BASED ON RACE-PACE"** supervised by **Dr. JORDAN SANTOS CONCEJERO** and **Dr. ARTURO CASADO ALDA**, and presented by Mr MARK KENNEALLY, and registered with the Department PHYSICAL EDUCATION AND SPOR

In Vitoria-Gasteiz on 17th of June, 2022

THE COORDINATOR OF THE DOCTORAL PROGRAMME

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ACTA DE GRADO DE DOCTOR O DOCTORA
ACTA DE DEFENSA DE TESIS DOCTORAL

DOCTORANDO DON Mark Kenneally

TITULO DE LA TESIS: *A novel approach to training analysis for distance runners based on race-pace*

El Tribunal designado por la Comisión de Postgrado de la UPV/EHU para calificar la Tesis Doctoral arriba indicada y reunido en el día de la fecha, una vez efectuada la defensa por el/la doctorando/a y contestadas las objeciones y/o sugerencias que se le han formulado, ha otorgado por___________________la calificación de:
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ACKNOWLEDGMENTS

In 2016 I got a notion to send an email to an unknown Academic in Spain, from my Ireland home, asking about the potential of doing a PhD with him, because I had some ideas on training for endurance running. When he got back to me with positive noises, and we had a skype call and agreed to make it work I was completely ignorant to the reality of what lay ahead. At the time I had one young child, and was working exclusively in my own clinic. The last 6 years has seen the addition of 3 more children, and a job in professional sport in Ireland. So, trying to manage time became the massive challenge. But never once did I waver in my enthusiasm for the project. I loved the subject and really believe in the path we have taken to help improve our understanding for training for endurance running.

So, my first massive thank you is to Jordan Santos-Concejero, my primary supervisor, who has been extremely patient with me. Missed timelines became a more than infrequent occurrence and he gave me the right shoves at the right time to try to keep me moving along. His attention to detail and breadth of knowledge has been absolutely crucial in getting this project to the stage it is at. Working with him has been eye-opening because of his efficiency and ability to get straight to the point of any meeting or topic. This ability to pick up on blindspots almost immediately has streamlined so many situations. Opportunities to mix more informally have unfortunately been limited but whenever we have done I have thoroughly enjoyed his company.

Arturo Casado is next on my list of people I wish to thank and acknowledge. His energy and endless interest in this topic area has meant that any relevant paper or topic have always been brought to my attention, and any inaccuracies, major or minor are pointed out. He linked us up with the group we studied, and the concept and theory of what we have studied was greatly influenced by him. When you speak to Arturo his passion for the sport and training is infectious and leaves you motivated to make a difference where you can.

Josu Gómez-Ezeiza has also been a great help during the process, helping with some of the practical components and also acting as a sounding board where required. I would like to thank Nic Bideau and his Melbourne Track Club, and in particular Stewart McSweyn, Jordy Williamsz, Ryan Gregson and Genevieve LaCaze. They allowed us access to their training sessions, philosophies, training diaries and more and without them this would not have been possible.

I have to say a massive thank you, and acknowledge the patience of my wife, Edel. With 4 kids over the last 6 years, and I working on this project and with a day job alongside this, she has been hugely supportive in ensuring that this get seen through to a finish. I could not have got through any of this without her. I need to acknowledge my kids at this point also. Cara, Luke, Conor and Jack provide huge fun and enjoyment and a welcome distraction at times when we got stuck.

Finally, over the last 5 years my family have been dealing with a long-term illness, and unfortunately in March of this year my father passed away. He was a massive influence on me, particularly with regard to education and furthering yourself. He was always completing course after course, right up until his illness became something which stopped him. Simply seeing this has undoubtedly been the inspiration around wanting to push more into education and to make contributions, and this thesis is dedicated to his memory.

SCIENTIFIC CONTRIBUTIONS

Peer-reviewed publications

Study 1:

Kenneally M, Casado A, Santos-Concejero J. The Effect of Periodisation and Training Intensity Distribution on Middle and Long-Distance Running Performance: A Systematic Review. *Int J Sports Physiol Perform* 13(9):1114-21. 2018

Quality indicators: ISI-JCR Impact factor: 3.979. 8/83 (Q1) SPORT SCIENCES 2018

Study 2:

Kenneally M, Casado A, Gomez-Ezeiza J, Santos-Concejero J. Training Intensity Distribution analysis by race pace *vs*. physiological approach in world-class middle- and long-distance runners. *Eur J Sport Sci* 21(6):819-26. 2020

Quality indicators: ISI-JCR Impact factor: 4.050. 21/88 (Q1) SPORT SCIENCES 2020

Study 3:

Kenneally M, Casado A, Gomez-Ezeiza J, Santos-Concejero J. Training characteristics of a World Championship 5000-m Finallist and Multiple Continental Record Holder over the year leading to a World Championship final. *Int J Sports Physiol Perform* 17 (1):142-6. 2022

Quality indicators: ISI-JCR Impact factor: 4.050. 22/88 (Q1) SPORT SCIENCES 2020

Congress communications

Oral presentation:

Training Intensity Distribution analysis by Race Pace Approach in World-Class distance runners

XXIII annual Congress of the European College of Sports Science (Dublin, Ireland). From 04/07/2018 to 07/07/2018

Other contributions

Kenneally M, Casado A, Santos-Concejero J. Training Intensity Distribution analysis by Race Pace Approach in World-Class distance runners. Book of Abstracts 23th annual Congress of the European College of Sport Science; Murphy M, Boreham C, De Vito G, Tsolakidis E (Eds.) SporTools GmbH, Feldblumenweg (Germany). 89-90. 2018

International experience and collaboration with institutions

Institution: Trinity College Dublin, Department of Anatomy

City: Dublin (Ireland) **Duration (weeks):** 16

Topic: Training prescription and periodization for elite endurance sport

Type of collaboration: Teaching and examination

ABSTRACT

Analysis of training for endurance sport is a topic which has been studied in the literature increasingly over the last decade. Analysis and planning of training, however, has historically been described as far back as the early 20^{th} century. As technology has improved and the means to monitor training have increased the concepts of training intensity distribution (TID) and periodisation have emerged. Training intensity distribution refers to proportion of training performed at different intensity levels. In order to make this more straightforward intensity zones have appeared in the literature. These zones have been delineated by various methods, most commonly lactate/ventilatory thresholds. Traditionally 3 zones have been described. TID, thus refers to the proportion of training performed in each of these zones. A number of TID models have been recognised:

- *Pyramidal*: the volume of training performed decreases in higher intensity zones
- *Polarised*: the volume of training performed in higher intensity zones is greater than in moderate intensity zones
- *Threshold:* the volume of training performed in moderate intensity zones is higher.

Periodisation then refers to the degree of change of training volume and TID over the course of a sport season. In recent years the recommendation of a polarised type TID has gained popularity because of research demonstrating its positive effects on physiological determinants associated with endurance performance. This fact serves as the background to this thesis. Anecdotally, it was observed that the best athletes in the world trained in a manner at odds with this contention and this thesis set out to examine this apparent contradiction, determine whether this was in fact the case, and then to attempt to understand reasons for this. We also presented a novel method to create training intensity zones, based on percentage of target race pace, which we felt reflected some of the practices being employed by the worlds' best coaches and athletes.

The thesis commences with a systematic review, which aimed to examine the current evidence for three primary training intensity distribution types: 1) Pyramidal training, 2)

Polarised Training and 3) Threshold Training. Where possible, we calculated training intensity zones relative to the goal race pace, rather than physiological or subjective variables. We searched three electronic databases in May 2017 (PubMed, Scopus, and Web of Science) for original research articles. After analysing 493 resultant original articles, studies were included if they met the following criteria: a) participants were middle- or long-distance runners; b) studies analysed training intensity distribution in the form of observational reports, case studies or interventions; c) studies were published in peer-reviewed journals and d) studies analysed training programs with a duration of 4 weeks or greater. Sixteen studies met the inclusion criteria, which included 6 observational reports, 3 case studies, 6 interventions and 1 review. According to the results of this analysis, pyramidal and polarised training are more effective than threshold training, although the latest is used by some of the best marathon runners in the world. Despite these apparent contradictory findings, this review presents evidence for the organisation of training into zones based on a percentage of race pace which allow for different periodisation types to be compatible. This approach requires further development to assess whether specific percentages above and below race pace are key to inducing optimal changes.

Based on this analysis we proceeded with an observational study of a group of world-class middle and long-distance runners, comparing the race-pace approach we propose to the traditional method of TID analysis via physiological metrics. The study aimed to analyse the training intensity distribution (TID) of a group of 7 world-class middle- and long-distance runners over 50 weeks using two different approaches to organise TID zones: 1) based on individual specific race pace and; 2) based on physiological parameters. Analysed training data included training volume, intensity and frequency. The average weekly volume for the group was 135.4 ± 29.4 km·week^{-1}. Training volumes for Z1, Z2 and Z3 were 88.5 ± 1.1%, 7.4 ± 0.8% and 4.1 ± 0.7% respectively for race-pace based approach, and 87.2 ± 1.2%, 6.1 ± 0.7% and 6.6 ± 0.9% respectively for the physiological approach. Differences were found between the approaches in Z2 (large effect, ES=1.20) and Z3 (moderate effect, ES=0.93). The approach based on race-pace zones produced pyramidal distributions in both middle- and long-distance runners across all phases of the season. The physiological approach produced polarised and pyramidal distributions depending of the phase of the season in the middle-distance runners, and pyramidal type TID across all phases of the season in the long-distance runners. The results of this study demonstrate that the training analysis in a world-class group of runners shows different TID when assessed relative to race pace *versus* to physiological zones. This highlights a potential deficiency in training analysis and prescription methods which do not make reference to specific performance. An approach which makes reference to both physiological and performance measures may allow for a more consistent and logical analysis.

We, therefore, saw that there was indeed some discrepancy between scientific recommendations and training methods of a group of world class athletes. However, it was clear that using a race pace approach in the manner we did would always lead to a more extensive Zone 2, incorporating a much wider range of paces than traditional physiological methods. We then looked deeper in our third article, using the training of an athlete who is world-class at distances from 1500m to 10000m, so spanned the "middle"- and "long"- distance track distances. 5000m was chosen as his reference target pace, as this was his preferred distance in the year of analysis, and also because it sat between middle- and long-distance.

In this case study the training of a world-class middle/long distance runner over a years' duration is presented. The training is analysed via 2 methods to define training intensity distribution (TID), 1) by physiological zones and; 2) zones based on race-pace. TID was analysed over the full season, but also over the final 6, 12 and 26 weeks to allow for consideration of periodization/phases of season. The results of both methods are compared. Other training data measured include volume and number of sessions.

The average weekly volume for the athlete was 145.8 ± 24.8 km·week^{-1}. TID by physiological analysis was polarised for the last 6 weeks of the season, but was pyramidal when analysed over the final 12, 26 and 52 weeks of the season. TID by race-pace analysis was pyramidal across all time points. The athlete finished 12th in the final of the World Championship 5000m and made the semi-final of the 1500m. He was ranked in the top 16 in the world for 1500m, 5000m and 10000m.

The results of this study demonstrate a potential flaw with recent work suggesting

polarised training as the most effective means to improve endurance performance. Here different analysis methods produced 2 different types of TID. A polarised distribution was only seen when analysed by physiological approach, and only during the last 6 weeks of a 52 weeks season. Longer term prospective studies, relating performance and physiological changes are suggested.

The main conclusion drawn from this thesis was that there is a gap between science and practice with regard to optimal training for performance in endurance running. A number of potential reasons were identified:

- Interventional studies examining this topic were often 6-12 weeks in duration. It was recognised that elite performance in endurance sport required years of consecutive of training phases, so conclusions drawn short interventional studies were likely to be of lower value.
- Many of the interventional studies did not examine running performance as an outcome, focussing on determinants of endurance performance. While these determinants are correlated with endurance performance, it is not precise, and there is an interaction effect between determinants which was not accounted for in many of these studies.
- Some of the evidence for polarised type distributions drew on interventions examining other sports, such as cycling or cross-country skiing. It is argued that the weight-bearing nature of running, as well as the standardised course and distances differentiated running, and facilitated training which focussed on specific paces.

Key words: Training Intensity Distribution; periodisation; distance running; race pace approach; lactate threshold; pyramidal; polarised; threshold

RESUMEN

El análisis del entrenamiento para deportes de resistencia es un tema que se ha estudiado cada vez más en la literatura durante la última década. El análisis y la planificación del entrenamiento, sin embargo, se han descrito históricamente desde principios del siglo XX. A medida que la tecnología ha mejorado y los medios para monitorear el entrenamiento han aumentado, han surgido los conceptos de distribución de la intensidad del entrenamiento (TID) y la periodización. La distribución de la intensidad del entrenamiento se refiere a la proporción de entrenamiento realizado en diferentes niveles de intensidad. Para hacer esto más sencillo, se han propuesto zonas de intensidad en la literatura. Estas zonas han sido delineadas por varios métodos, más comúnmente umbrales de lactato/ventilación. Tradicionalmente se han descrito 3 zonas. TID, por lo tanto, se refiere a la proporción de entrenamiento realizado en cada una de estas zonas. Se han reconocido varios modelos TID:

• *Piramidal*: el volumen de entrenamiento realizado disminuye en las zonas de mayor intensidad
• *Polarizado*: el volumen de entrenamiento realizado en las zonas de mayor intensidad es mayor que en las zonas de intensidad moderada
• *Umbral*: el volumen de entrenamiento realizado en zonas de intensidad moderada es mayor.

Entonces, la periodización se refiere al grado de cambio del volumen de entrenamiento y TID en el transcurso de una temporada deportiva. En los últimos años, la recomendación de un TID de tipo polarizado ha ganado popularidad debido a la investigación que demuestra sus efectos positivos sobre los determinantes fisiológicos asociados con el rendimiento de resistencia. Este hecho sirve de base para esta tesis. Como anécdota, se observó que los mejores atletas del mundo entrenaban de una manera contraria a esta afirmación y esta tesis se propuso examinar esta aparente contradicción; determinar si este era realmente el caso y luego intentar comprender las razones. También presentamos un método novedoso para crear zonas de intensidad de entrenamiento, basado en el porcentaje del ritmo de carrera objetivo, que sentimos que refleja algunas de las prácticas empleadas por los mejores entrenadores y atletas del mundo.

La tesis comienza con una revisión sistemática, cuyo objetivo es examinar la evidencia actual de tres tipos principales de distribución de la intensidad del entrenamiento: 1) Entrenamiento piramidal, 2) Entrenamiento polarizado y 3) Entrenamiento de umbral. Siempre que fue posible, calculamos las zonas de intensidad de entrenamiento en relación con el ritmo de carrera objetivo, en lugar de las variables fisiológicas o subjetivas. Se realizaron búsquedas en tres bases de datos electrónicas en mayo de 2017 (PubMed, Scopus y Web of Science) en busca de artículos de investigación originales. Después de analizar 493 artículos originales resultantes, los estudios se incluyeron si cumplían con los siguientes criterios: a) los participantes eran corredores de media o larga distancia; b) estudios que analizaron la distribución de la intensidad del entrenamiento en forma de informes de observación, estudios de casos o intervenciones; c) los estudios se publicaron en revistas revisadas por pares y d) los estudios analizaron programas de entrenamiento con una duración de 4 semanas o más. Dieciséis estudios cumplieron con los criterios de inclusión, que incluyeron 6 informes observacionales, 3 estudios de casos, 6 intervenciones y 1 revisión. Este enfoque requiere un mayor desarrollo para evaluar si los porcentajes específicos por encima y por debajo del ritmo de carrera son clave para inducir cambios óptimos. Según los resultados de este análisis, el entrenamiento piramidal y polarizado son más efectivos que el entrenamiento de umbral, aunque este último es utilizado por algunos de los mejores corredores de maratón del mundo. A pesar de estos hallazgos aparentemente contradictorios, esta revisión presenta evidencia para la organización del entrenamiento en zonas basadas en un porcentaje de ritmo de carrera que permite que diferentes tipos de periodización sean compatibles. Con base en este análisis, procedimos con un estudio observacional de un grupo de corredores de media y larga distancia de clase mundial, comparando el enfoque de ritmo de carrera que proponemos con el método tradicional de análisis TID a través de métricas fisiológicas.

El estudio tuvo como objetivo analizar la distribución de la intensidad del entrenamiento (TID) de un grupo de 7 corredores de media y larga distancia de clase mundial durante 50 semanas utilizando dos enfoques diferentes para organizar las zonas TID: 1) basado en el ritmo de carrera específico individual y; 2) basado en parámetros fisiológicos.

Los datos de entrenamiento analizados incluyeron el volumen, la intensidad y la frecuencia del entrenamiento. El volumen promedio semanal del grupo fue de 135.4 ± 29.4 km·semana^{-1}. Los volúmenes de entrenamiento para Z1, Z2 y Z3 fueron 88.5 ± 1,1 %, 7.4 ± 0.8 % y 4.1 ± 0.7 % respectivamente para el enfoque basado en el ritmo de carrera, y 87.2 ± 1.2 %, 6.1 ± 0.7 % y 6.6 ± 0.9 % respectivamente para el enfoque fisiológico. Se encontraron diferencias entre los enfoques en Z2 (efecto grande, ES=1.20) y Z3 (efecto moderado, ES=0.93).

El enfoque basado en zonas de ritmo de carrera produjo distribuciones piramidales en corredores de media y larga distancia en todas las fases de la temporada. El enfoque fisiológico produjo distribuciones polarizadas y piramidales dependiendo de la fase de la temporada. en los corredores de medio fondo, y TID de tipo piramidal a lo largo de todas las fases de la temporada en los corredores de fondo. Los resultados de este estudio demuestran que el análisis del entrenamiento en un grupo de corredores de clase mundial muestra diferentes TID cuando se evalúa en relación con el ritmo de carrera frente a las zonas fisiológicas. Esto pone de manifiesto una deficiencia potencial en el análisis del entrenamiento y los métodos de prescripción que no hacen referencia a un rendimiento específico. Un enfoque que haga referencia tanto a medidas fisiológicas como de rendimiento puede permitir un análisis más coherente y lógico. Por lo tanto, vimos que efectivamente había cierta discrepancia entre las recomendaciones científicas y los métodos de entrenamiento de un grupo de atletas de clase mundial. Sin embargo, estaba claro que usar un enfoque de ritmo de carrera como lo hicimos siempre conduciría a una zona 2 más extensa, incorporando una gama mucho más amplia de ritmos que los métodos fisiológicos tradicionales. Luego profundizamos en nuestro tercer artículo, utilizando el entrenamiento de un atleta de clase mundial en distancias de 1500 m a 10000 m, por lo que abarcamos las distancias de pista de distancia "media" y "larga". Se eligieron los 5000 m como su ritmo objetivo de referencia, ya que esta era su distancia preferida en el año de análisis, y también porque se encontraba entre media y larga distancia.

En este estudio de caso se presenta el entrenamiento de un corredor de media/larga distancia de clase mundial durante un año. El entrenamiento se analiza a través de 2 métodos para definir la distribución de la intensidad del entrenamiento (TID) 1) por zonas fisiológicas y; 2) zonas basadas en el ritmo de carrera.

El TID se analizó durante la temporada completa, pero también durante las últimas 6, 12 y 26 semanas para permitir la consideración de la periodización/fases de la temporada. Se comparan los resultados de ambos métodos. Otros datos de entrenamiento medidos incluyen el volumen y el número de sesiones. El volumen semanal promedio fue de 145.8 ± 248 km·semana^{-1}. El TID por análisis fisiológico fue polarizado durante las últimas 6 semanas de la temporada, pero fue piramidal cuando se analizó durante las últimas 12, 26 y 52 semanas de la temporada. El TID por análisis de ritmo de carrera fue piramidal en todos los puntos de tiempo. El atleta terminó 12º en la final del Campeonato del Mundo de 5000m y llegó a la semifinal de los 1500m. Estuvo clasificado entre los 16 mejores del mundo en 1500m, 5000m y 10000m.

Los resultados de este estudio demuestran una falla potencial con trabajos recientes que sugieren que el entrenamiento polarizado es el medio más efectivo para mejorar el rendimiento de resistencia. Aquí diferentes métodos de análisis produjeron 2 tipos diferentes de TID. Solo se observó una distribución polarizada cuando se analizó mediante un enfoque fisiológico, y solo durante las últimas 6 semanas de una temporada de 52 semanas. Se sugieren estudios prospectivos a más largo plazo, que relacionen el rendimiento y los cambios fisiológicos. La principal conclusión extraída de esta tesis fue que existe una brecha entre la ciencia y la práctica con respecto al entrenamiento óptimo para el rendimiento en carreras de resistencia. Se identificaron varias razones potenciales:

- Los estudios de intervención que examinaron este tema a menudo duraron de 6 a 12 semanas. Se reconoció que el rendimiento de élite en el deporte de resistencia requería años de fases de entrenamiento consecutivas, por lo que es probable que las conclusiones extraídas de estudios de intervención breves sean de menor valor.
- Muchos de los estudios de intervención no examinaron el rendimiento de carrera como un resultado, centrándose en los determinantes del rendimiento de resistencia. Si bien estos determinantes están correlacionados con el rendimiento de resistencia, no es preciso y existe un efecto de interacción entre los determinantes que no se tuvo en cuenta en muchos de estos estudios.

• Parte de la evidencia de las distribuciones de tipo polarizado se basó en intervenciones que examinaron otros deportes, como el ciclismo o el esquí de fondo. Se argumenta que la naturaleza de la carrera con carga de peso, así como el curso y las distancias estandarizados diferenciaron la carrera y facilitaron el entrenamiento que se centró en ritmos específicos.

Palabras clave: Distribución de la Intensidad del Entrenamiento; periodización; carreras de distancia; enfoque de ritmo de carrera; umbral de lactato; piramidal; polarizado; límite

LIST OF SYMBOLS AND ABBREVIATIONS

TID: Training Intensity Distribution

LT: Lactate Threshold

LT1: First lactate threshold

LT2: Second lactate threshold

vLT: Velocity at lactate threshold

mmol·L^{-1}: Millimoles per litre

$\dot{V}O_{2max}$: Maximal oxygen uptake

% $\dot{V}O_{2max}$**:** percentage of the maximum oxygen uptake

vVO_{2max}: Velocity at $\dot{V}O_{2max}$

RE: Running economy

SUL: Finnish Sports Federation

MAS: Maximal Aerobic Speed

SD: Standard deviation

ES: Effect size

km: Kilometre

(h:mm:ss): hours: minutes: seconds

km·h^{-1}: Kilometres per hour

IJSPP: International Journal of Sports Physiology and Performance

VT1: First ventilatory threshold

VT2: Second ventilatory threshold

%HR: Percentage of the maximum heart rate

IAAF: International Amateur Athletics Federation

WA: World Athletics

RP: Race-Pace

RCT: Randomised Controlled Trial

XC: Cross Country

MP: Marathon pace

BW: Body weight

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INTRODUCTION

‘If you only read the books that everyone else is reading, you can only think what everyone else is thinking’

Haruki Murakami

1 Introduction

1.2 General Introduction to the Topic

This thesis studies the organisation of training of endurance runners. The 3 published papers[1–3] start with a review of the current literature to establish what is recommended by experts in the field. Two studies then examined the training of an elite group, and of a world-class individual, and compare their training performance to what is recommended based on scientific research. The reasoning behind examining the literature and current practice of an elite group is based on a recurrent, admittedly anecdotal, observation that the worlds' best athletes do not currently perform training which reflects what is recommended scientifically. Potential reasons for this conflict will be discussed in detail, with very recent work cited to help explain why such a gap exists[4]. The specific physiological characteristics associated with endurance performance[5–8] will be discussed as part of this, and all training analysis in the published papers are framed with these physiological characteristics to the fore.

As well as discussing the gap mentioned above from a scientific perspective, and to provide further context to the proposed problem, the history of training for endurance running will first be presented[9,10]. This demonstrates an interesting pattern. A cycle of fluctuating between lower volume/high intensity training and higher volume/reduced higher intensity training and the current situation will be presented within this historical context. In addition to this, evidence will be presented to potentially further explain why there is a gap between science and practice based on research from the field of coaching science. This will reflect coaches' attitudes towards, and difficulty with, developments in sports science which may be potentially practice altering. "Survivorship bias" will also be considered as part of this, whereby these attitudes and difficulties with sports science and physiology developments may actually be affected by the fact that the experience of having success as an athlete or coach in itself lends weight to the idea that utilised methods are most appropriate, rather than engaging in a thorough examination of methods to ensure that they are rigorously tested[11–14]. Paper 1 in this thesis: "The effect of periodisation and training intensity distribution on middle- and long-distance running performance: A systematic review"[3], examined the background research on this topic, specifically as it pertained to distance running, as opposed to other endurance sports such as cycling and cross-country skiing, which also feature prominently in the literature. The reason for making this distinction explicit was to acknowledge the unique biomechanical properties associated with running i.e. weight-bearing locomotion. This stands in contrast to sports like cycling or cross-country skiing, in which recovery happens quicker[15]. This paper serves as an introduction to the issue mentioned above and provides the context in which to consider it. Before starting into much of what is described above, however, some essential recurrent terms and themes are defined and contextualised in the following sections.

1.3 Background and Definitions

Endurance running training and performance is a much studied and debated topic[16–23], and in recent years the organisation of training for endurance performance has been studied extensively and 2 recurrent concepts have emerged:

1. Training Intensity Distribution (TID)
2. Periodisation

These 2 concepts have proved more contentious than the establishment of consensus regarding factors that limit endurance, and specifically running, performance[5,24]. These factors include lactate threshold (LT)[6], defined either as the velocity at which a non-linear increase in blood lactate occurs, the maximal lactate steady-state or the velocity corresponding to a blood lactate concentration of $4mmol.l^{-1}$[25] (further sub-division of the lactate threshold into first (LT1) and second (LT2) thresholds can be made, traditionally defined as the velocities corresponding blood lactate concentrations of 2 and $4mmol.l^{-1}$ [26]); maximal oxygen uptake (VO_{2max})[8,27]; velocity at VO_{2max} (vVO_{2max})[8,27]; and running economy (RE)[7], defined as steady-state VO_2 at a given submaximal speed or as the VO_2 per unit distance[28] . More recently the concept of "durability" has emerged [29]. This concept has been focussed on the change of behaviour of the factors mentioned over time when running. A specific example may be that heart rate at LT2, as measured by incremental lab testing, may differ significantly to heart rate at similar levels of lactate at 10 minutes, 20 minutes or 30 minutes into a training session or performance. The notion of this fatigue resistance of specific characteristics is one that is relatively recent.

The training process has thus been considered the manipulation of intensity, duration and frequency of training sessions with the intention of improving the physiological characteristics described above and/or performance[17]. The link between performance and physiology has been studied[30,31] but no clear relationship has been established between proportional changes in physiological characteristics and performance. This lack of relationship underpins the current thesis as it provides the opportunity for training methods to be employed which are purely empirical, ignoring research on physiology. Further to this, as will be discussed later, coaches consistently report scientific research as ranking low on their means of changing or affecting their practice[11]. Training and coaching, and the quantification of the same, have however, been guided by the creation of different training intensity zones and training intensity distribution thus refers to the relative volume or quantity of training performed in these different zones.

1.3.1 Training Intensity Distribution (TID)

This refers to the relative amount of training done at various levels of intensity within a defined timeframe-usually a week or training cycle[32]. Numerous systems have emerged to classify "zones" of intensity. These zones may be based on:

a. Physiological characteristics such as lactate levels[6], ventilatory patterns[33], oxygen uptake[5], anaerobic system function[34].
b. Subjective factor such as session goal or session rate of perceived exertion (RPE-Borg Scale)[35].
c. Performance factors such as specific race pace. [36]

TID Zones

Classically 3 zones have been described[16]:

1. Zone 1: Low-Intensity training
2. Zone 2: Moderate-intensity training
3. Zone 3: High-Intensity training

Zone 1 comprising low-intensity training. Physiologically this zone has been described as lying below the first lactate or ventilatory threshold. From a performance standpoint marathon pace will usually lie towards the upper end of this zone in less well-trained runners.[37]

Zone 2 refers to moderate-intensity training. This intensity has been physiologically described as falling between lactate or ventilatory thresholds. From the perspective of performance, the upper bound of this zone is usually considered to refer to the pace sustainable for events of 40-60-minute duration[38]. Both marathon and half-marathon pace will fall within this zone in well-trained runners.

Zone 3 is high-intensity training. It refers to training performed at intensities above the second ventilatory or lactate threshold. Race performance at intensities in this zone will typically be sustainable for less than 30 minutes[38].

In recent years authors have employed systems of describing TID using more zones, up to 7 in some studies[20]. The creation of these systems has, in some cases attempted to relate performance and physiological metrics in a manner which reflects the training methods and performance being examined within a retrospective study.

Types of TID

3 types of TID's have been recognised in the literature on this topic:

a. Pyramidal
b. Polarised
c. Threshold

A *pyramidal* TID is seen as the classical training method employed in distance running[17]. It involves the performance of decreasing volumes of training at increasing levels of intensity. This may involve the performance of 80% of training volume in Zone 1, 15% in zone 2, and 5% of training volume in zone 3. The history of training for endurance running will be discussed in a later section but it reflects the training first seen in Finnish and Swedish runner in the 1910s-1930s, and later developed by coaches in New Zealand and Australia in the 1960s and 1970s.

A *polarised* TID involves the performance of increased volume of training in zone 3, at the expense of zone 2. Polarised training has gained favour at different periods over the last 100 years, as will be discussed later. For example, it may involve 80% in zone 1, 5% in zone 2, and 15% in zone 3. Recent studies comparing TID's effects have often returned favourable results for polarised type TID's. For reasons which will be discussed later, we feel that there are problems with this conclusion.

A *threshold* TID exhibits the performance of larger volumes of training in zone 2, in comparison to the other 2 zones. It is not an approach which has gained favour historically within the context of distance running, as will be seen later. However recent work has shown that the use of threshold intensities in training for distance running is positively correlated with world ranking and world-class performance[23,39]

1.3.2 Periodisation

This refers to the organisation and planning of training over longer periods of time with a specific end target or goal in mind[40]. It is generally considered to be based upon the General Adaptation Syndrome described by Hans Selye as early as the 1930s[41]. It can be seen as the variation of TID and volume over longer cycles of training. So, if a training cycle lasts a week, and is described by TID, then periodisation may describe the variation in this TID over a longer period of time, and will detail the change in intensity, volume or mode of training, usually linking this variation to a training target. So, for example a training week prescribing 80% zone 1, 12% zone 2, and 8% zone 3 can be said to have a pyramidal TID. Periodisation will then describe planned changes in this distribution in order to achieve a certain target-the plan may suggest maintaining TID in this proportion for a certain period of time to achieve a target, e.g. the development of VO_2 max, which then may be followed by a a new "period" of training with a potentially different TID; in order to develop more or different characteristics e.g. lactate threshold etc. In this way it can be seen that TID is a narrower concept than periodisation. TID focusses only on intensity, whereas periodisation encompasses types of exercise also. Periodisation is often considered with planning in mind whereas TID is often considered as a descriptive means to describe a training block. Periodisation is a concept that has come under scrutiny in recent years[42]. Much of the basis for periodisation has been developed from Selye's work on the General Adaptation Syndrome[41], and 2 main methods of periodisation are seen in the literature:

1. Traditional periodisation
2. Block periodisation

Traditional Periodisation

The more traditional method of periodisation has focussed on developing different training abilities simultaneously throughout the season[43]. This method is characterised by a gradual progression from higher training volume and lower intensity to- reduced volume and higher training intensity, thereby shifting from general training to training that is more specific as the competition period approaches. However, it can be further subdivided into linear and non-linear periodisation, whereby the progression or variation in training may not follow a graded increase or reduction in type or intensity, but may focus on development of characteristics via most effective means.

Traditionally 3 types of time divisions, or cycles, are seen:

1. Microcycle: usually lasting a period of 1-2 weeks
2. Mesocycle: usually a longer period e.g. 4-6 weeks
3. Macrocycle: usually a season plan, so may be 6-12 months in duration

Various names have emerged to describe these cycles e.g Base phase, build phase, peaking phase, depending on the target of the training period.

Under the traditional periodisation process 3 periods have emerged:

1. General Preparation Period
2. Specific Preparation Period
3. Competition Period

Different types of exercise will populate these periods under this system, and it gets its name because each period of training, or block, will focus on a single quality or training adaptation. The types of exercises are:

1. General Preparatory Exercises-these are exercises/training sessions that do not imitate the competitive event and do not train the specific systems associated with the event.
2. Specific Preparatory Exercises-these are exercises/training sessions that do not imitate the competitive event but train the major muscle groups and physiological systems
3. Specific Development Exercises- these are exercises/training sessions that repeat the competitive event but in separate parts
4. Competitive-these are exercises/sessions that are identical or almost identical to competition event.

Block Periodisation

Block periodisation is a more recent concept[40] and is applied most famously in power sports, with Bondarchuk-a hammer-throwing coach- one of those responsible for further developing the concept, along with Issurin more recently[44,45]. . The basic premises of Block Periodisation are: the employment of highly concentrated phases of training and the residual effect; sequencing of the blocks logically to benefit from the residual effects. The approach can be employed to focus on a single factor or multiple factors. Phases during Block Periodisation are named:

1. Accumulation
2. Transmutation
3. Realisation

Block periodisation has not been frequently used in endurance running, as will be described in the evolution of endurance training concepts. Part of the reason for this will surely lie in the fact that endurance athletes tend to maintain high training volumes all year around and have variation mostly within the higher intensity work.[18–20] However, a relatively recent [43] systematic review and meta-analysis of papers on block periodisation of endurance training suggested it may be an alternative strategy for consideration in the future. The authors of this paper, however, did note that the papers included in the analysis were small studies with generally low methodological quality, and advised caution in assigning too much weight to the findings.

More recently the basis for periodisation has been called into question in a paper by Kiely[42]. He points out that Selye's work on the general adaptation syndrome from the 1930's-whereby stress was considered as a predictable biological phenomenon-has been undermined, and now, for example there are demonstrable effects of non-physical factors on physiological stress responses, and that these stress responses are individualised and context specific. He argues therefore, that if the basis for organising training is on Selye's work, that it has become outdated and a new approach to training organisation may be appropriate.

This point is perhaps reflected in the passages preceding this, as the concepts of TID and periodisation are relatively similar in their parameters-they both consider volume, intensity, duration and frequency of training, with the main differentiating factor being that periodisation seems to be considered over a longer period of time and requires that titles or targets be placed on its periods or phases. The use of TID within endurance sport is also one that has a significant body of evidence behind it[16,18–22,32,36,46–48]. The approach we have taken below in our published studies is to consider TID models and volume over varying periods of time, without considering targets for specific periods or phases.

1.3.3 The History of Training for Endurance Running

Any study examining the organisation of training for endurance runners would seem to be incomplete without at least mentioning the history and evolution of training. If we contend, as we do, that many coaches working at elite level in distance running are not actively using scientific studies to inform their methods then it stands to reason that history and experience must do so. Therefore, understanding this history may be helpful in shaping an approach to progress the training process from a scientific perspective. In this context 3 authors, named below, provide direction on where to look for historical sources on the history of training. The fact that many of the scientific analytic processes, which may provide information on physiological characteristics relevant to performance, have only become more readily available and convenient over the last 40 years also means that a large portion of training theory and practice must be bounded in convention and empiricism.

Steve Magness has helpfully detailed the evolution and history of training on his website scienceofrunning.com[49], framed in a volume vs intensity debate, and Tim Noakes in his tome "Lore of Running" also provides useful information on the training of many of history's most famous distance runners[9]. Finally, Andrew Renfree, via his website andrewrenfree.wordpress.com helps to shape the following paragraphs through his articles which also deal with the history of training for endurance running[10]. All 3 authors direct us toward the original sources for all of the information.

Magness notes a cyclical nature to the evolution of training over the last 100 years, whereby the accepted training methods of any particular era have flipped from being higher volume/lower intensity to lower volume/ higher intensity repeatedly. He starts as far back as the 1800s when the best runners of the time did a lot of long walking with small volumes of fast running interspersed. In the early part of the 20th century walking remained a staple part of training for many of the best distance runners in the world. However, by 1910/1911 athletes such as Clarence DeMar, 7 time winner of the Boston Marathon, documented running 160 km/100 miles per week at times. DeMar was the subject of a number of studies by physiologists at the Harvard Fatigue Laboratory, which gave early indications of some of the key determinants of endurance performance. They found that he had superior running economy, lactate dynamics and threshold, and a very high $\dot{V}O_{2max}$.

In the 1910s, 1920s and 1930s the world of distance running was dominated by Finnish runners. The most famous of these was Paavo Nurmi, who won 9 gold and 3 silver medals across 3 Olympic Games. His training methods continued to include long walks, up to 4 hours, particularly during the winter, but started to incorporate increasing volumes of running- with documentation of volumes of running again in excess of 160 km/100 miles per week provided by a booklet by Jaako Mikkola-coach of the 1920 and 1924 Finnish Olympic teams-and translated for Tim Noakes for his book. It may be that the hard winters experienced in Finland may have been part of the reason for the volume of walking performed during their base period, or it may well be that the coaches and athletes felt that high volumes of walking prepared them to be able to tolerate the running which would follow. The Finnish methods of these times were also progressive in that they started to incorporate steady and faster running, both in the form of continuous runs and intervals. The information provided by Mikkola demonstrates sessions such as 6-8 x 100m followed by 5000m at “75%”. Interval sessions for these athletes tended not to have repetitions longer than 6-800m, and if longer bouts of steady/fast running were being performed during training they were done as individual time trials. This era of Finnish running saw the country finish in the top 5 of the Olympic medal table for 3 successive Olympic Games between 1920 and 1928, with athletes such as Nurmi, Ville Ritola, Elias Katz, Albin Stenroos, Hannes Kohlemainen, Harri Larva and Tolve Loukola winning gold medals.

Following on from this, German physiologist, Woldemar Gerschler, saw the success of the Finnish training regime, and determined that it could be improved by altering the manner in which faster running was performed. He devised a system based on heart rate. This system essentially involved raising the heart rate to 180bpm and allowing it to recover to 120bpm. Thus, structured interval training was born. He had his athletes run high volumes of moderate interval work day after day, and this influence is seen into the 1940s and 1950s with the training of Emil Zatopek-multiple Olympic champion across the 1948 and 1952 Games. He remains the only man in history to win all 3 of the 5000m, 10000m and marathon titles, setting 18 world records from 5000m to marathon across his career. In the 1950s, however, a dichotomy emerges via the influence of Franz Stampfl. He advocated a lower volume higher intensity approach to intervals. He influenced athletes such as Roger Bannister, his famous staple workout of 10x440yds off 2 minutes recovery being directly influenced by Stampfl.

In the 1960s and 1970s coaches like Percy Cerutty and Arthur Lydiard began to recommend training concepts which were quite different to the methods described above. As far back as 1947 a German medical doctor named Ernst Van Aaken published an article recommending long duration low intensity exercise as the route to good health. Alongside the health benefits he proposed, he used this philosophy to coach endurance athletes, the most famous of whom was Harald Norpoth, Olympic silver medallist over 5000m in 1964, and one-time 2000m world record holder. Ninety percent of Norpoths training was done at heart rates between 120 and 150bpm, with the other 10% made up of faster running, but he advocated running these at the target race pace, in fractions of racing distance. Examples of this were 3x1000m at 5000m race pace, 3x500 at mile pace. On top of this he recommended short bouts of sprint training occasionally-approximately 50m in length.

There are similarities between Van Aakens' methods and to what was advocated by Cerutty and Lydiard. Lydiard, particularly, was in favour of blocks of high volumes of easy to steady running, by way of building a "base" in early season. They both used interval and steady running in increasing volumes as a season progressed. This conscious recognition of the interaction between intensity and volume was further evidenced by a gradual move towards alternating between easier days and harder days as the training philosophies evolved. Up to this point training weeks for endurance athletes would see endless days of interval training. Now coaches were starting to prescribe easier days and harder days, and the basic structure of training, as we would now consider it took shape, with a mixture of intensities and volumes over different days. The concept of periodisation also became rooted in the process, by way of the "base' phase, followed by transitions to preparatory and competitive phases. This approach implicitly seemed to acknowledge that as training volume increased training intensity had to decrease in some way to avoid athletes from becoming burnt out.

At around the same time, between the 1950s and 1970s there was an interesting parallel approach being used by a Hungarian coach named Mihaly Igloi. His beliefs about training were very similar to the likes of Lydiard and Cerutty, in that he believed that a superior aerobic capability was the key to successful endurance performance. However, in stark contrast, he believed that the means by which to develop this was using short intervals, so he has become synonymous with interval training. He had significant success in the US, where he relocated to in the 1950s, most notably Bob Schul winning the 5000m at the 1964 Olympics. It is also interesting to note that Igloi's athletes would run high volumes, up to 100mpw, and that many of the intervals were very much submaximal in nature, with his express goal often to tax the aerobic mechanics. So although the methods utilised by these 2 groups of coaches differed significantly they very much agreed on their perception of the required "physiology" to achieve success in endurance sport.

There is an interesting piece of work carried out by a Finnish Masters student, called Mikko Leinonen, reflecting on Finnish endurance running coaching during this period of the 1970s (translated by Alain Guettinger) which further adds to this overview of the evolution of training for endurance running[50]. After the earlier successes described for Finnish athletes up to the 1930s, the 1950s and 1960s were relatively unsuccessful. The Finnish Sports Federation (SUL) decided to invest heavily in the coaching structures for endurance running, to try to rekindle their success. The visit of Mihaly Igloi to Finland in 1962 was seen as a significant point as it influenced coaches such as Kari Sinkkonen during the 1960s, but success still eluded the nation. In 1967 the Finnish athletic federation entered a contract with Arthur Lydiard to shape endurance running training in the country. Leinonen surmises that Lydiard managed to overturn the practices of Igloi in the country by the end of the decade. A tour of the country lecturing coaches on training practices ensured that his principles and methods became well known throughout the country, and Leinonen reflects that in the 1970s "the Finnish 'coaching line' was in line with Lydiards teachings, but more refined and better suited to Finnish conditions". The paper also presents training volumes and TID's of the top Finnish runners of the 1970s. The TID of the 9 athletes reported was pyramidal, as would be expected with Lydiard influenced training, and was also characterised by relatively high volumes of running. Lasse Viren, the multiple Olympic champion for example, averaged 8129 km in 1974, his highest year of the 1970s. Over his most successful time period: 1972-1976 Viren ran 7383 km, 7414 km, 8130 km, 4356 km and 6486 km respectively. The years with lower volumes were characterised by injuries, and this period included 5000m and 10000m gold at both the 1972 and 1976 Olympic Games.

At this same time this high-volume approach was being used throughout the southern hemisphere, and while coaches such as Cerutty and Lydiard are credited with its inception, other Antipodean coaches employed similar methods, including Arch Jelley, John Dixon, John Davies, among other. Using these methods athletes such Dick Quax, John Walker, Rod Dixon, Derek Clayton, Peter Snell, and Murray Halberg achieved Olympic and global success. Coaches in the US and UK also started to use these methods-

Bill Bowerman the most famous in the US, guiding athletes like Steve Prefontaine. In the UK the most famous proponent of this approach was a coach named Harry Wilson, who coached Steve Ovett to Olympic medals and world records. In the late 1970s and 1980s, however, a new philosophy also emerged. It was a coach named Peter Coe who favoured this approach. His son, Seb Coe, Ovetts' rival through the 1970s and 1980s, trained in this new manner, to great success.

Peter Coe's approach favoured less volume, and a training pace system based on race paces. This system was devised by a British coach called Frank Horwill and it was based around motor learning more so than the traditional metabolic basis for training prescription. Horwill felt that performance was based on being familiar with specific race pace[51]. To this end, Coe also included structured strength training and plyometrics, modalities not widely described by earlier coaches. He also embraced developing sports science methods to help guide some of the training/training paces based on metabolic zones. These included lactate monitoring and VO_2 max assessment. His approach gained favour throughout the 1980's and 1990's, particularly in the UK and US. Magness points out that this approach resulted in a massive shift away from what had been a steady development in coaching practice over half a century, based on what could now be measured: "we said goodbye to simple progression of our training and instead focussed on magical zones". The following years, characterised by this new approach, saw relative failure for those employing it. Athletes from the US and UK particularly became less prominent in the medals at global championships.

It should be pointed out, however, that at this time, African distance running was on the rise. It is therefore very difficult to attribute the failures of athletes from the UK and US during this period solely to the shift in training methods. The emergence of Kenyan and Ethiopian distance runners en masse followed glimpses of their talent in the 1960s and 1970s with Abebe Bikila, Henry Rono, Miruts Yifter. However, some other countries continued to have some success during this emergence. Italy produced 2 Olympic marathon champions, Germany produced an Olympic 5000m gold and silver medallist. These successes during this period were characterised by higher volume, less intense training. Interestingly, one of the coaches involved in the Italian training-Luciano Gigliotti-describes some of his approach in an interview with the (then) IAAF publication

NSA in 2007. He notes that the 2 Italian marathon gold medallists ran between 220 and 280 km per week, and ran much of their more intense training at paces close to marathon pace. This approach has famously been used by Renato Canova, a contemporary of Gigliotti's, in coaching African athletes over the last 10-15 years. Over the same time period American and British athletes such as Galen Rupp, Meb Keflezighi, Mo Farah and Paula Radcliffe have reverted to higher volume training again, and we have seen them become relevant globally once again.

At this point I would like to acknowledge the fact that much of the historical review has focussed on information regarding male athletes. This is a point not lost, and unfortunately reflects the historical situation. The intention was not to focus purely on male endurance athletes but the longest womens' distance event in the Olympic Games remained the 1500m until 1980. In 1984 the 3000m and marathon were introduced for women. From around this time on information became available on training methods by the world's best females[22]. Examples include Grete Waitz and Ingrid Kristiansen, who in the early 1980s also followed higher volume training methods. As will be seen later the studies we have conducted have included females as part of the analysis.

1.3.4 Science in the History of Endurance Training

The information presented above does not tell us why the pattern seen occurred. Was the evolution seen organic, or was it influenced by scientific advancement along the way? A 2011 article in Sports Science by Stephen Seiler summarises a history of endurance testing in athletes, and signposts much of the seminal work done in the 20th century in the advancement of exercise physiology/sports science[52]. From AV Hill's work in the 1920s and 1930s[53], demonstrating the existence of a "VO_2 max" through to the work of David Costill in the 1970s[54], whereby the 3 key determinants of endurance performance; VO_2 max, lactate threshold, and running economy, were now being systematically collected and profiled. Although technology has made the collection of these variables easier over the last 40 years, essentially the exercise testing and profiling process was advanced and refined over the period from the 1950s to the 1980s and best practice has not changed significantly since then.

To what extent, if any, did these developments affect the evolution? This is a very difficult question to answer as it seems likely that a person involved in coaching human performance would have at least a passing interest in the science of human performance, but certainly up to the 1960s and 70s the coaches mentioned above, as pioneers in training advancement, did not make specific reference to an influence of scientific testing and profiling on their methods. This is likely due as much to access as it is to any other reason. As suggested by Magness, Peter Coe appears to be one of the first of the coaches mentioned who overtly referenced exercise physiology/sports science as a cornerstone of his philosophy. Indeed Arthur Lydiard, perhaps the most famous of the coaches mentioned, describes his methods as having been based on personal trial and error[55]:

"*For years I ran many kilometers trying to find the correct balance for my conditioning training. I knew you could both undertrain and overtrain in both mileage and effort. I ran from extremes of 80 to 500 kilometers a week at close to my best aerobic effort*".

In the 1980s, however, institutions such as the Australian Institute of Sport have started to be created, with departments dedicated to practical sports science, so over the last 40 years the testing and profiling process has become more integrated into the experience of many athletes. The African distance running powerhouses of Kenya and Ethiopia, however, continue to lack widespread facilities of this sort.

1.4 Theoretical Framework of the Thesis

1.4.1 Ideological Basis

It was, in fact, Canova's methods referenced above, which sparked the idea for the current thesis. As a student of exercise physiology/training science, and as an athlete; terms such as lactate threshold, anaerobic threshold, ventilatory threshold, VO_2 max, running economy become very familiar. However, their practical application, and relationship to real-life performance, have remained less focussed anecdotally. This anecdotal "feeling" was further strengthened in examining the literature on optimal training for endurance running. As will be discussed below, more recent work has suggested that the approach employed empirically by coaches of the current best athletes in the world remain somewhat at odds with science[48,56–59]. If we take the current Olympic marathon champion and world record holder as an example; 6 weeks of his training leading to a world record performance in Berlin was made available in 2017 and analysed by Trent Stellingwerff on Twitter. Volumes in excess of 180 km per week were seen, and the TID for the time period was 73%/19%/8% in Zone 1/2/3[60]. Current recommendations suggest that a polarised approach, with minimal training performed in zone 2 are consistent with scientific best practice to improve the determinants of endurance performance[48,56]. Yet the training methods utilised by Kipchoge were consistent with those we observed in practice by the best athletes in the world, and actually with the documented training history of some of the best athletes in the world[23,61]. This apparent contradiction sparked a desire to explore further. The starting point was to try to remove as many biases as possible. As an athlete, the tendency was to be somewhat dismissive of scientific endeavour as less applicable to the worlds' elite, as they were "outliers". However, this seemed a lazy approach. To assume that some of the most intelligent people involved in sport science globally were simply wrong did not sit well. Equally it seemed incorrect to think that the experience of the coaches of the best athletes in the world should be diminished in value in favour of methods which when employed previously, as history has shown above, were followed by periods of reduced success for the coaches and athletes which employed them. Many of the coaches in question, such as those working for sporting brands or national organisations, now have ready access to sports science facilities and expertise readily, yet there is still something of a disconnect between practice and the evidence base.

But do we then dismiss the scientific research being carried out? To me it seemed that part of the problem lays in the type of questions being asked, both initially, then by way of study design. Athletic development, from a coaching/performance perspective, requires planning and structuring details of training over long periods of time. Many of the studies referenced below draw conclusions on relatively short-term interventions, which then examined change in physiological variables rather than real-world performance. A coach may well use the scientific principles recommended but real-world situations rarely create linear predictable responses in humans, and on an individual basis, sports science leaves a lot of gaps which coaches must fill in using whatever information they can. So, the interesting questions to me became:

1. What parts of sports science best practice are currently applied in the training of the worlds' elite athletes?
2. Why?
3. What parts are not?
4. Why?

The worlds' elite seemed a logical place to start the examination as the assumption is that they are doing something right to allow themselves to be the best in the world, but I was perfectly happy to be shown that there was no justifiable, evidence-based design-planned or unplanned-to what they were doing. An opportunity presented itself, which allowed access to a group of athletes based in Australia. The training of this group seemed to be more consistent with the high volume, pyramidal methods described above. Over a period of 10-15 years the group had athletes who qualified for global and continental championship finals, and who won medals at World and Continental championship, both male and female.

1.4.2 Coaches' Attitudes

What do we know about the attitudes of coaches and sports scientists towards each other more generally, given the evolution of training for endurance running described above? What does the academic literature tell us about how coaches view and use scientific advancements in this field? Could differences seen here help to explain the problem?

A South African paper from 2018 surveyed 202 coaches working across the country[12]. These coaches felt that knowledge of sports science was important for them to perform their role, but that researchers needed to translate their research into easily understandable language to have greatest impact. The survey used in this paper was first used in a 2007 paper which examined the attitudes of Australian coaches and sports scientists[14]. Interesting to note is the different resources which coaches and researchers used to keep up-to-date with the latest developments in their sports. Coaches again ranked workshops and coaching conferences highly, however they rated scientific literature low on their list, whereas sports scientist ranked scientific journals and conferences as their most important resources. Another interesting finding-granted it was 15 years ago-was that sports scientists felt that coaches did not need to have sports science knowledge. Coaches felt very strongly that they did, and both felt, as in the South African paper, that researchers needed to translate scientific journals to easily understandable language.

A 2008 Canadian paper asked 3 questions of coaches[13]: 1) how do they perceive sports science, 2) what sources do they consult when looking for new ideas, and 3) what barriers do coaches encounter when trying to access new information. 205 coaches responded, across a variety of sports. 75% of coaches in this paper agreed that sports science contributed to the development of the sport. However, only 4% reported that they were likely to consult peer-reviewed journals when looking for new ideas. As in the previous papers the most highly utilised resources were conferences and workshops, along with their peers. The coaches in this paper felt that sports science was largely not exploring the ideas that they felt were most important.

The same questions were asked of Turkish coaches in a 2015 paper[11], with similar answers returned. Again, coaches strongly felt that sports science contributes to sport but that there are gaps between what coaches are looking for and the research that is being conducted. It was seen that conferences were the main source of new information, and that scientific publications ranked low on coaches' sources of knowledge.

A recent study by Parmar and Jones surveyed 32 coaches practicing globally[62], coaching athletes ranging from recreational to international level. Relevant to the current conversation, the coaches were asked specifically about their use of interval training with their athletes. Most coaches reported learning about interval training from their own training and coaching books, but that the most valuable sources of education sources for interval training were ranked as scientific literature, coaching courses and workshops. So it seems that in this study, at least, that coaches were aware of scientific literature regarding their training methods. However, the majority of coaches then reported that they most frequently prescribed training intensity using race pace, rather than physiological methods. This apparent cognitive dissonance rings true with the points made above, whereby coaches with access to the best sports science facilities and expertise in the world continue to prescribe training based largely on experience and history.

So the disconnect mentioned above is reflected in the studies done examining coaches experiences with sports science. This may help to provide answers to questions 3 and 4 above but it does not necessarily justify the gap. If the main reason for poor application of sports science theories to practice are because coaches do not look to the right sources, or do not understand the science then the logical step is to make available resources in a more readily understandable manner. However, without understanding what current actual training methods at an elite level consist of then it is very difficult to reach any conclusion. To this end, when formulating the thesis question, I chose to use the methods of Renato Canova in coaching African marathon runners as another example of elite training methods. The reason for this was two-fold:

1. At the time of formulation his runners were dominating the marathon majors
2. He made readily available online, and through a book he co-authored, his training philosophy and methods.

As will be seen below the philosophy is full of scientific sounding terms and training methods, but little scientific referencing is provided for it, other than textbook basic physiology. The methods, however, were clearly bearing fruit, and provided an interesting start-point for a discussion.

1.4.3 The Methods of Renato Canova

The sources for these methods were from the 1999 IAAF book Marathon Training: A Scientific Approach[37], written by Enrico Arcelli and Canova, and from posts on running forums on the internet by him, which largely repeat the content of the book, but provide some more specific detail on workouts/examples, and on the sequencing of training progression. As suggested above Canova describes a number of training zones in quasi-scientific terms:

- Aerobic Power: Canova seems to equate this with paces approaching but below the traditional lactate threshold, so at the upper end of Zone 2

- Anaerobic Endurance: seems to equate with paces just above the lactate threshold and does not seem to differ massively from Aerobic Power in the actual paces described, but probably sits at the lower end of Zone 3.
- Aerobic Endurance/Capacity: equates with traditional Zone 1/low intensity training
- Anaerobic Power: definitively refers to classical Zone 3 training.
- Muscle Efficiency: most closely resembles speed/power work-it encompasses short hills, bounding and drills.

Canova then describes the process for planning training for a marathon in 3 phases:

1. General Preparatory Phase: lasting 6-8 weeks and with the intention of “increasing muscle efficiency through running technique exercises and gym sessions”. The running performed during this period is mostly done in Zones 1 and 2, through continuous or progressive runs.

2. Fundamental Phase: lasting 8-10 weeks, and focussing firstly on “Aerobic Power Endurance”. He describes this as either an intensification of long Zone 1 runs for those athletes with subjectively described good endurance or an extensification of Zone 2 runs for an athlete who has a high lactate threshold. Other targets include development of anaerobic endurance through interval sessions just above lactate threshold, maintance of aerobic endurance/capacity through continuous submaximal runs approximating Zone 2, and maintenance of muscle efficiency through strength and technique work

3. Specific Preparatory Phase: lasting 6-8 weeks, Canova states that the goal is to use “our consolidated qualities” (physiological) to prepare for performance in an event, and is focussed on specific goal marathon pace. So, most workouts described are related to the goal marathon pace, and usually fall within 95-105% of this pace. This usually corresponds with Zone 2 intensities.

He carries on to describe workout types which he deems to affect particular qualities (Table 1). From this, we can see that, on the face of it, Canova follows a training structure not dissimilar to the previously described block periodisation. The reality, however, is that he notes that each phase will have a mixture of workout types, and in addition a very high volume of "regeneration" runs. During these athletes run for 50-90 minutes at self-selected easy paces (Zone 1). This means that Canova's approach performs 70-80% of their total training volume at low/Zone 1 intensities, consistent with TID's discussed above. For marathon runners under Canova, their training would follow a very Pyramidal type TID, because of the abundance of work done around marathon pace, i.e. in Zone 2. This held true, on further examination, for athletes competing over 5000m and 10000m, again due to the proximity of race paces for these distances to the lactate threshold.

Canova's approach to middle-distance (defined here as incorporating distances from 800m to 5000m) running does not deviate philosophically from the marathon training described above. The information on middle-distance training has been gathered from interviews with Canova, and his posts on running websites. At its essence he describes the training process for training for distances from 800m to marathon as functions of "specific extension". That means that the desired race/event speed is usually achievable by an athlete training for the event for a period of time-even when not in shape, and that the training process seeks to extend that ability to run at that pace as far as the desired distance. So specific training for middle distance events will definitively fall in zone 3. While table 1 describes in detail the descriptions of workouts used for marathon training there is a slightly simpler global description of workout categories which he uses (Table 2). Similar to the training described above for the marathon preparation for middle distance events is split into three periods by Canova, after an "Introductive Period" common to all distances. In middle distance these periods are described as:

1. Fundamental Period: lasting 8 weeks. Mileage and intensity gradually increase over this period and workouts are mainly of the fundamental type described in Table 2. Interval workouts described as "aerobic endurance" workouts are also prescribed. An example for an 800m runner here would be 8x400m off 2 minutes recovery, at a pace approximately 20% slower than race pace.

2. Special Period: lasting 8 weeks, focussing on developing both speed and endurance for the specific event. Workouts will generally be targeted at paces above 105% race pace, or between 90-95% of race pace. Continuous or tempo runs are

completed at paces approximating 90% of race pace. Otherwise the intervals are as described below:

3. Specific Period: lasting 8-10 weeks. The goal is to optimise physiological and psychological preparation for race-pace, and workouts between 95 and 105% or race-pace are performed. Volume of work at race-pace will be high, and recovery/regeneration is emphasised as being all-important. Thus, it is easy to see why this would become training resembling polarised TID.

Table 1. Session/Workout classifications of Renato Canova, sourced from Arcelli (2003) and Letsrun.com

Workout Label	Workout Type	Examples	Target (Per Canova)	Relevant Intensity Zone
Aerobic Endurance	Continuous	45-180 mins	Breathing balance comfortable	Zone 1
	Continuous	45-90 mins progressive	Increase in pace at fixed intervals	Zone 1-Zone 2
Aerobic Power	Continuous	20-40 mins	Pace 104-107% MP	Zone 2
	Long Intervals	3 x 5 km with 3 mins recovery	Pace 103-107% MP	Zone 2
Anaerobic Endurance	Short to Medium Intervals	10 x 1 km with 2 mins recovery	Pace 106-110% MP	Zone 2-Zone 3
Specific Marathon Endurance	Continuous	18-25 km	Pace 100% MP	Zone 2
Specific Extensive Endurance	Intervals	4 x 5 km with 1 km recovery	Interval Pace 100-102% MP Recovery Pace 85-95% MP	Zone 2
Specific Intensive Endurance	Intervals	8 x 1 km with 1 km recovery	Interval Pace 103% MP Recovery Pace 97% MP	Zone 2-Zone 3
Specific Endurance Long Run	Continuous	32 km continuous	Pace 98-100% MP	Zone 2

Table 2. Workout classification for middle distance of Renato Canova. Sourced from Letsrun.com personal contribution.

Workout Label	Workout Type	Examples	Target (Per Canova)	Relevant Intensity Zone
Regeneration	Continuous	45-180 mins	Breathing balance comfortable, reduce lactate concentration	Zone 1
Fundamental	Continuous or Interval	30 minutes steady 3 x 10 minutes	Pace 1.15-1.5 times slower than event, depending on event	Zone 1-Zone 2
Special	Continuous or Interval	10 x 1 km with 2 mins recovery	Pace over 110% specific race pace or at approx. 95% specific race pace	Zone 2-Zone 3
Specific	Interval	2 x (5x300)-800m 8 x 400-1500m	Pace 95-105% specific race pace	Zone 3

As we explored the training of other world class athletes, such as Eliud Kipchoge, described above, the Australian group who formed our participants for our papers, and groups running under various commercial shoe companies in the US, it became clear that similar methods were being employed by many of the worlds' best athletes. Athletes competing from distances as short as 1500m were using these methods. Consistently we saw athletes running volumes in excess of 150 km per week, and performing more of their "quality" workouts in Zone 2 than Zone 3. Yet, as referenced above, on reviewing the relevant interventional literature it was repeatedly recommended that a polarised type distribution, with higher volumes of work in Zone 3 than Zone 2 was superior. It was this that seemed to elicit the best physiological adaptations, at least over the timeframes involved in the studies. Recently a point-counterpoint argument in Medicine and Science in Sports and Exercise[63,64] examined this topic, arguing both sides. Foster *et al*[64], arguing for polarised training, recognise that the difference between a polarised and pyramidal TID may actually be quite subtle, and that in fact event specificity may explain some of the contradictions-in other words that the targeted performance reference distance will have different specific demands. A study which uses 5 km or 10 km performance as a reference, distances which at the elite/sub-elite level fall in zone 3, may demonstrate superiority of a polarised type TID because specific race pace happens to fall in zone 3.

On the other side Burnley *et al*[63] make the case that many of the studies which describe polarised training are problematic for various reasons, including interventional duration, method used to quantify TID etc. This will be discussed in more detail later, as our systematic review deals specifically with this topic. However, as way of background to the reason for developing this thesis it is important to mention it now. In addition to the observed anecdotal findings we noted, some observational work existed in the literature which further highlighted the issue. A 2016 paper by Tjelta detailed training volumes of elite distance runners globally and corroborated the high volumes we observed[19]. While this of itself was not contradictory to a polarised distribution, Casado *et al* found that when the deliberate practices of many of the best Kenyan and Spanish athletes in the world were examined, it was volume of easy running and "tempo" running (Zone 2) which differentiated the best athletes in the world[23,39]. So, it seemed that there was an issue with the labelling of training volumes in Zone 2 as less beneficial, since many of the best athletes in the world were doing sessions at this intensity. And as outlined above in Canova's methods, the reason for training at this intensity was most commonly that it was perceived as being the most effective way to affect the velocity at lactate threshold, one of the earlier referenced performance determinants in endurance running.

At this point the obvious question was: What is this perception based on, and is it correct? A 2007 paper by Esfarjan *et al* did elicit improvements in vLT and 3000m time trial performance using intervals at and above vVO_2 max, so firmly in Zone 3, at odds with the perception[65]. Perhaps a 1982 paper by Yoshida *et al* influenced this perception. In this paper, training at the lactate threshold elicited significant improvements in the lactate threshold, and on $\dot{V}O_{2max}$[66]. This was also found in a 2011 paper by Enoksen *et al* using well-trained middle-distance runners, although the intensities prescribed in this study were around the lactate threshold, in Zone 2[67]. However, as will be described later, a number of studies following this found greater improvements in LT and other physiological characteristics using Zone 3 intensities rather than Zone 2 intensities[4,48,56]. Therefore, although there was at least some justification academically for using threshold intensities to elicit improvements, there was also a clear case for coaches to consider the use of higher intensity work for this reason also. Because training in this context is an ongoing process, it seemed logical then that perhaps the 2 approaches were not necessarily mutually exclusive, and in fact may both serve purposes at different times of a training cycle. This was a point considered in a 2015 study by Muñoz *et al*, in which they considered whether race pace represented the best specific intensity for "peaking" for competition, very much in line with Canova's approach[36]. They observed equal improvements in 10-km time for groups using race-pace based intensities and high intensities. They did observe some differences in physiological responses over the time course studied. This further raised some interesting questions-although we know for a long time the physiological factors which affect endurance running performance, namely VO_2 max, lactate threshold and running economy; the relative contribution of these factors to performance has not been well studied.

1.4.4 The Training Groups' Philosophy and Methods

Conversations with the group's coach allowed for understanding and documentation of his methods[68]. The starting point for the conversations was that it was felt that there was a disconnect between sports science and training practice, and he offered an opinion on it. Many of his athletes underwent somewhat regular (annual or semi-annual) lactate profiling and VO_2 max assessment as part of their agreements with National organisations. It was felt that some value was derived from this, by way of a regular checkpoint on physiological progress, and the heart rates which delineated Zone 2 were used for their "threshold" sessions. He noted that often the changes seen were things that he felt he could see through their performance e.g. changes in MAS/vVO_2 max were reflected by improvements in 3000m/5000m PB's.

He described 3 subgroups within the group (Sample training weeks for the groups are seen in Tables 3-4 below):

1. Long-distance/Marathon: the approach to preparing for a marathon is broken into 2 main phases. During the first phase the target is to build towards a good performance over a 10k or half marathon. During the second phase, which starts approximately 10-12 weeks before the marathon, training becomes more focussed around marathon pace. Examples of training weeks for both of these phases are detailed below (Table 3)

2. Long-distance track 5000m/10000m: these athletes begin preparation in October. A sample training week from the time period October to February is detailed below. In

late January/February these athletes would usually perform a test race over 1500m or 3000m “to see where their speed endurance is at”. Their training week then changes slightly and is detailed below also. What is interesting about the track sessions during this period is that the target times are prescribed using target race pace as a guide (Table 4).

3. Middle-distance track 800m/1500m. The coach describes athletes in the group who specialise at these distances as usually being “more aerobic” so interestingly their training structure is similar to the long-distance track subgroup from October to February, with differences then in their track sessions from February onwards. However, it is worth noting that their total volumes remain relatively high (Table 4).

The coach notes that weekly training volumes for the group are usually in excess of 140km for the males and 120km for the females. This difference mainly comes about because easy running sessions are prescribed for durations rather than distances so there is a tendency for the males to run slightly faster on these runs. Weekly volume can increase to over 180 km per week also, particularly if athletes are preparing for a marathon. Consistency of training at these volumes, season on season, year on year is repeatedly highlighted as a key to success, in the coaches’ opinion.

The coach describes his approach as being on based on the successes and knowledge first evident in the 1960s-as described above. It is founded on creating and maintaining an “aerobic base”. Harder/track workouts are described as being designed to maintain aerobic fitness gained while practicing what athletes need to do to be successful in their races. He notes that even during racing/competitive seasons he purposely plans long runs and anaerobic threshold/tempo runs; one of each is performed every 10 days or so. The weekly training volume is never reduced significantly for long periods of time either, only to allow 2-3 days taper before or recovery after races.

Table 3. Sample training weeks for marathon group for different phases of preparation

	Marathon Training Phase 1	**Marathon Training Phase 2**
Monday	am 60 minutes easy pm 30 minutes easy	am 50 minutes pm 50 minutes
Tuesday	am 8 x 1 km at HMP with 1 min rest pm 30 minutes easy	am 90 minutes with 10k easy, 10k at threshold HR, and cool-down pm 35 minutes easy
Wednesday	am 50 minutes pm 30 minutes	60 minutes easy
Thursday	90 minutes with 10k easy, 10k at threshold HR, and cool-down	am 50 minutes pm 50 minutes
Friday	am 60 minutes pm 30 minutes	22-25 km progressive with last 10km at MP
Saturday	am 6 x 800m hills pm 30 minutes easy	am 50 minutes pm 50 minutes
Sunday	120 minutes long run easy	am 150 minutes, with last 10k at marathon effort on hills pm 30 minutes easy

Table 4. Sample training weeks for the track groups for different phases of preparation.

	Track Group Oct-Feb	Long-Distance Track Feb onwards	Middle-Distance Track Feb onwards
Monday	am 60 minutes pm 30 minutes plus drills and strides	am 60 minutes pm 30 minutes plus drills and strides	am 60 minutes pm 30 minutes plus drills and strides
Tuesday	am 8 x 1 km at 10km race pace with 1-minute recovery pm 30 minutes	am Track session-Example: *-1600m at 10km RP* *Lap jog (2:00)* *-4x400 at 3k RP (30 secs recovery)* *Lap jog (2:00)* *-1600m at 10km RP* *Lap jog (2:00)* *-4x400 at 3k RP (30 secs recovery)* *Lap jog (2:00)* *-1600m at 10km RP* pm 30 minutes easy	am Track session-Example: *-6 laps progressive 10k to 3k pace* *Lap jog (2:00)* *-3x800-Lap 1: 3k pace, Lap 2: 5 seconds faster (lap recovery)* *5 minutes recovery* *-500m with last 300m at 800m RP* *3 minutes recovery* *-300m at 800m RP* *Lap jog (2:00)* *-6x200 at 800m RP*
Wednesday	am 60 minutes pm 30 minutes	am 60 minutes pm 30 minutes	am 60 minutes pm 30 minutes
Thursday	am 9km at threshold HR pm 30 minutes easy	am 9km at threshold HR pm 30 minutes easy	am 9km at threshold HR pm 30 minutes easy
Friday	60 minutes easy	60 minutes easy	60 minutes easy
Saturday	am 6 x 800m hills pm 30 minutes easy	am Hill session-Example: *-2km threshold (flat)* *2:00* *-4x350m hill* *Reps 1 and 3: 3km race effort,* *Reps 2 and 4: max effort* *2:00* *-2km threshold (flat)* *2:00* *-4x350m hills as above* *2:00* *-2km threshold* pm 30 minutes easy	am Hill session-Example: *-2km threshold (flat)* *2:00* *-4x350m hill* *Reps 1 and 3: 3km race effort* *Reps 2 and 4: max effort* *2:00* *-2km threshold (flat)* *2:00* *-4x350m hills as above* *2:00* *-2km threshold* pm 30 minutes easy
Sunday	105 mins easy	105-120 minutes easy	105-120 minutes easy

2

METHODOLOGY

‘There ain’t no sin and there ain’t no virtue. There’s just stuff people do.’
John Steinbeck

2 METHODOLOGY

2.1 Publication 1: The Effect of Periodisation and Training Intensity Distribution on Middle and Long-Distance Running Performance: A Systematic Review

2.1.1 Experimental approach to the Problem

A literature search was conducted on May 6, 2017. The following databases were searched: PubMed, Scopus, and Web of Science. Databases were searched from inception up to May 2017, with no language limitation. Citations from scientific conferences were excluded.

2.1.2 Literature Search

In each database the title, abstract and keywords search fields were searched. The following keywords, combined with Boolean operators (AND, OR) were used: "training intensity distribution running", "periodisation running", "training intensity distribution endurance", "periodisation endurance", "polarised training running", "pyramidal training running", and "threshold training running". No additional filters or search limitations were used.

2.1.3 Inclusion Criteria

Studies were eligible for further analysis if the following inclusion criteria were met; a) participants were middle- or long-distance runners (studies with triathletes or any other kind of athletes were excluded); b) studies analysed training intensity distribution and/or periodisation in the form of observational reports, case studies or interventions; c) studies were published in peer-reviewed journals and d) studies analysed training programs with a duration of 4 weeks or longer.

Two independent observers reviewed the studies and then individually decided whether inclusion was appropriate. In the event of a disagreement, a third observer was consulted to determine the inclusion of the study. A flow chart of the search strategy and study selection is shown in Figure 1.

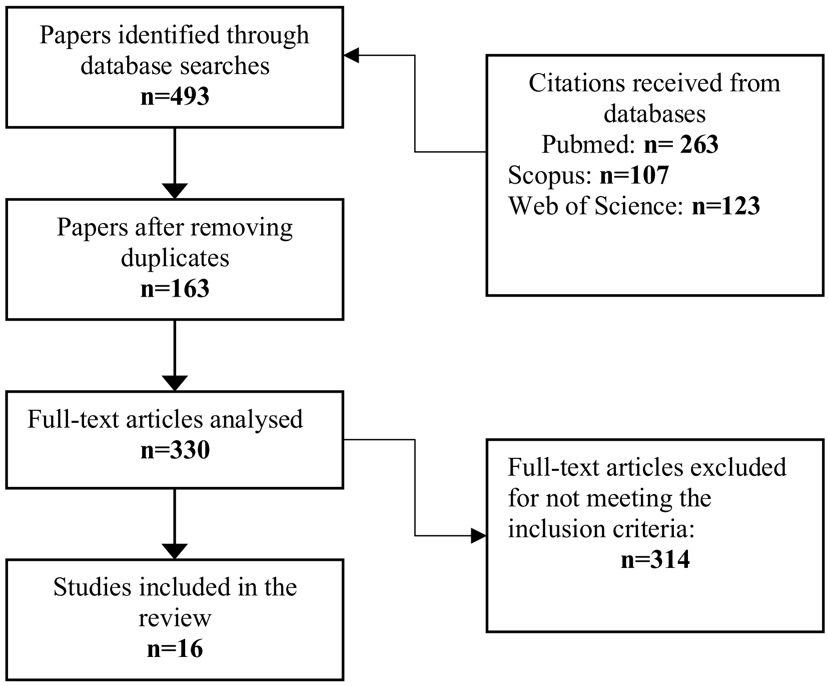


Figure 1. Flow chart of search strategy and selection of articles.

2.1.4 Quality Assessment

Oxford's level of evidence[69] and the Physiotherapy Evidence Database[70] (PEDro) scale were used by 2 independent observers in order to assess the methodological quality of the articles included in the review. Oxford's level of evidence ranges from 1a to 5, with 1a being systematic reviews of high-quality randomised controlled trials (RCT) and 5 being expert opinions. The PEDro scale consists of 11 different items related to scientific rigor. The items include random allocation; concealment of allocation; comparability of groups at baseline; blinding of subjects, researchers and assessors; analysis by intention to treat; and adequacy of follow-up. Items 2-11 can be rated with 0 or 1, so the highest rate in the PEDro scale is 10, and the lowest, 0. Zero points are awarded to a study that fails to satisfy any of the included items, and 10 points to a study that satisfies all the included items.

2.1.5 Statistical Analysis

All values were expressed as mean ± standard deviation (SD). In studies with sufficient data, TID determined by traditional physiological parameters was compared to a race-pace based TID using a Cohen *d*.[71] Training zones for the race-pace approach were determined as following; zone 1: volume performed at <95% of goal race pace, zone 2; volume performed between 95% and 105% of goal race pace, and zone 3; volume performed at >105% of goal race pace. The magnitude of differences, or effect size (ES) of this comparison was interpreted as small (>0.2 and <0.6), moderate (>0.2 and <0.6), moderate (≥0.6 and <1.2), large (≥1.2 and <2) and very large (≥2.0) according to the scale proposed by Hopkins *et al.*[72]

2.2 Publication 2: Training Intensity Distribution analysis by Race Pace *vs.* Physiological approach in World-Class middle- and long-distance runners

2.2.2 Participants

Seven elite runners (3 men and 4 women) participated in this study. During the analysed period, all participants but one achieved top-8 in the previous major athletics championships. The athletes are coached by the same coach and are part of the same training group, which has been consistently producing athletes who qualify for major athletics events (Commonwealth Games, World Championships and Olympic Games). The coach has more than 15 years of experience training multiple international medallist athletes. The athletes were sub-grouped into middle-distance runners (800-1500m athletes) and long-distance runners (5000m-10000m athletes). All participants provided written informed consent. The Ethics Committee for Research on Human subjects of the University of the Basque Country UPV/EHU (CEISH-UPV/EHU 94/2017) approved this study, which was conducted in compliance with the principles of the Declaration of Helsinki (2013).

2.2.3 Data Collection and Analysis

A detailed daily log of training data prescribed by the coach and updated by the athletes was provided. Data were collected over a 50-week training period. The season was divided into two preparation cycles, one of 28 weeks for the World Athletics Championships (April 2017 to August 2017), followed by 20 weeks until the Commonwealth Games (April 2018), with two weeks of active rest in between. Additionally, anthropometric and physiological data were collected following each preparation phase. A maximal incremental treadmill test was conducted to determine the physiological profile of the athlete. The protocol consisted of increments of 1-$km \cdot h^{-1}$ every 5 min, starting at 14 $km \cdot h^{-1}$ for women and 15 $km \cdot h^{-1}$ for men, respectively, until volitional exhaustion. During the test, oxygen uptake (VO_2) was continuously measured using a gas analyser system (Oxycon Pro, Eric Jaeger, Hoechberg, Germany). $\dot{V}O_{2max}$ was defined as the maximum 30s VO_2 value recorded and vVO_{2max} was defined as the minimum speed at which this volume was reached. Blood samples were collected from the earlobe during the last 30s of each increment to analyse lactate concentration (The Edge^{TM} Lactate Analyser). Lactate thresholds were calculated using the ADAPT method[73].

Analysed training data included training volume, intensity and frequency, as well as session intention. Then, TID was organised and compared based on race-pace[9] (Z1: <80% race pace; Z2: 80-95% race pace; Z3 >95% race pace) and physiological zones (Z1: <LT1; Z2: LT1 to LT2; Z3 >LT2).

2.2.4 Training Philosophy for the Group for the Period

The coach of the group observed employed an outcome-based process to his coaching. It was focussed primarily on the achievement of race performance, as defined by time achieved in a specific event, or by championship performance. Therefore the 2 main outcomes which training for this group is targeted toward are:

1. Time achieved over a specific distance i.e. mean race pace over a specific distance
2. Ability to finish a race in a championship at a specific pace, defined externally, based on either what is required to make a final or win a medal, depending on the athlete. The coach defined these as pace over last 400m for 800m/1500m, and over the last 1000m for 5000/10000m

The coach prescribed sessions for the athletes using a combination of heart rate and specific pace. Heart rate was used in the prescription of “threshold” focussed sessions, and was used to ensure that the athletes maintained their heart rate at a level consistent with Z2, as measured in the treadmill testing. Pace based sessions were prescribed relative to specific race paces, informed by the coaches' experience. The athletes did perform some short hill sessions at certain phases of the year. These sessions were interval sessions with interval duration of no more than 800m. For these sessions the athletes were instructed to run at 5k effort. For the purposes of analysis these sessions were included in Z3 for both physiological and race-pace based approach.

2.2.5 Statistical Analysis

All values were expressed using a mean ± standard deviation (SD). The volume of training in race pace-based zones were compared to each other and to physiological based zones using Cohen *d*[71]. The magnitude of differences, or effect size (ES) of this comparison was interpreted as small (>0.2 and <0.6), moderate (≥0.6 and <1.2), large (≥1.2 and <2) and very large (≥2.0) according to the scale proposed by Hopkins *et al*.[72]

2.3 Publication 3: Training Characteristics of a World Championship 5000m finalist, and multiple continental record holder over the year leading to a World Championship final

2.3.2 Subject

The case study athlete is a male middle-distance runner. Over the timeframe examined the athlete was 23-24 years old. The athlete's height was 1.88 m and body weight was ~67 kg.

2.3.3 Training and Competition Data

The subject provided all training data for the period October 2018 to October 2019. Training data consisted of distance (km), duration (h:mm:ss), session intention (Easy/Threshold/Interval). Race schedule and results were also provided by the athlete.

The athlete did physiological testing just before the 2-week break preceding the examined timeframe, and results are presented in Table 5. This was an incremental treadmill test, starting at 15 km·h^{-1}, and increasing by 1 km·h^{-1} every 5 mins until volitional exhaustion. O_2 uptake was constantly measured using a gas analyser system (Oxycon Pro, Germany). Blood samples were collected from the earlobe during the last 30s of each increment to analyse lactate concentration (The Edge™ Lactate Analyser). LT1 and LT2 were again calculated using the ADAPT method[73]

2.3.4 Calculation of volumes in each intensity zone

A database was created with 1 km·h^{-1} increments or "buckets". All sessions were analysed and the volume of running performed at different speeds was calculated. This volume was then allocated to the different speed "buckets". Where sessions were continuous the average pace was used-unless the athlete stated that a change of pace of greater than 1 km·h^{-1} occurred within the session. In this instance the volume was split accordingly. For interval sessions the average pace of the repetition was used. However, if the athlete stated that a repetition had change of pace within it, the detail of this was recorded, and the volume allocated accordingly. The time period studied was then subdivided into 4 periods to demonstrate change in training structure over the whole year. These 4 periods were: 52 weeks, 26 weeks, 12 weeks, and 6 weeks. These time periods were chosen arbitrarily.

Table 5. Physiological and Performance characteristics of the participant

Characteristics	
Height	1.88 m
Weight	67 kg
$\dot{V}O_{2\ peak}$	73.5 $mL\cdot kg^{-1}\cdot min^{-1}$
Velocity at LT1	18.3 $km\cdot h^{-1}$
Velocity at LT2	20.3 $km\cdot h^{-1}$
Running Economy at LT1	193 $mL\cdot kg^{-1}\cdot km^{-1}$
Running Economy at LT2	198 $mL\cdot kg^{-1}\cdot km^{-1}$
1500m PB (achieved during period)	3:31.81
3000m SB/PB	7:38.22/7:34.79
5000m SB/PB	13:05.63/13:05.23
10000m PB (achieved during period)	27:23.80

PB, personal best; SB, season best; LT1, first lactate threshold; LT2, second lactate threshold

2.3.5 Physiological Approach:

Zone 1 (Z1), Zone 2 (Z2) and Zone 3 (Z3) were defined as: <vLT1(18.3 $km\cdot h^{-1}$); between vLT1 and vLT2 (20.3 $km\cdot h^{-1}$); and above vLT2, respectively. These values were obtained from the athletes testing data provided.

2.3.6 Race-Pace Approach:

Z1, Z2 and Z3 were defined as described previously[4] (RP was defined as 23.1 $km\cdot h^{-1}$, the pace of the athletes' 5000m personal best): Z1<80% RP (18.5 $km\cdot h^{-1}$), Z2 80-95% RP (18.5-21.95 $km\cdot h^{-1}$), Z3>95% of RP.

2.3.7 Session Intention and types

The coach prescribed sessions for the athlete using a combination of heart rate and specific pace:

- *Easy* sessions were all non-specific running sessions, and were Z1 regardless of analysis type.
- *Threshold* sessions were prescribed using heart rate to ensure that the athlete maintained his heart rate at a level consistent with physiological Z2, as measured in the treadmill testing.
- *Interval* sessions were prescribed relative to specific race paces,. These sessions included both Z2 and Z3 intensities by both methods of analysis. The athlete did perform some short hill sessions at certain phases of the year. These sessions were interval sessions with interval duration of no more than 800m. For these sessions the athlete was instructed to run at 5-km effort. For the purposes of analysis these sessions were included in Z3 for both physiological and race-pace based approach.

3

HYPOTHESES & AIMS

'You're bound to get ideas if you go thinking about stuff'

John Steinbeck

3 Hypotheses and Aims

3.1 Hypothesis

2 recent articles, one a review, and one an editorial, by the same lead author; Thomas Haugen, have eloquently framed the problem presented, albeit after the research question was framed. The review article examined "the science and practice of training world-class 800m and 1500m runners"[61]. The author notes that

"despite an increasing amount of research devoted to middle-distance training, it is reasonable to argue that the developments in these disciplines have not been driven by sports scientists. Publicly available 'recipe books' and training diaries based upon the practical experience and intuition of world-leading athletes and coaches have become important and popular sources of best practice training information and framework development for the international middle-distance community."

The paper then goes on to present an integration of training information gleaned from training diaries and books, and presents it using 2 zone scales, a 5 zone and 9 zone scale, based on a combination of physiological qualities and specific coaching intention for sessions. 2 case studies are then presented, one of an Olympic champion 800m runner, the other a European champion 1500m runner. Their training at different stages of the season is analysed, with differences seen between different stages of the year, and between the 2 events. Polarised TID's of varying degree are seen across the season in the 800m runner, with a mixture of polarised and pyramidal TID's seen over the season in the 1500m runner.

The 2nd article reinforces some of the points made above, in that it suggests that best-practice coaches are an untapped resource in sport science research[74]. It references the fact that in the more than 1100 studies published in the IJSPP (as an example) between 2015 and 2021, less than 0.5% of the studies used coaches as participants.

The current thesis was born out of a similar thought process to what is elucidated here. The path to the question was slightly different, however. I was an athlete myself, to start. My supervisors were also athletes. One of them is the European 1500m champion referenced in the previous paragraphs. The problem, as I saw it, was with the practical utilisation of physiological profiling. Physiological testing/profiling had become a regular part of my training process, but the benefit, or difference that this profiling made to my prospective training planning was not clear to me. It seemed like it was being used more as verification of the effectiveness of my training process, and this was a common feeling among athletes I spoke to. I spent most of my career assuming that I was just doing it poorly, and that other coaches and athletes (whom I hadn't spoken to) knew something that I didn't about the use of profiling to plan training. When I started to examine the research, however, I became less convinced.

My own training would have fallen into the pyramidal type TID for the most part, and was relatively high volume. Peak training weeks were typically in excess of 175km regularly. From what I could see with other training groups and athletes, this was pretty standard. Therefore, it surprised me to read the more recent papers studying interventions on training structure, and repeatedly finding that a polarised distribution was better at eliciting changes in key physiological qualities, and in some cases, performance. Was what I had done for so many years completely wrong? And therefore, was everyone else doing it wrong also? If science told us that in order for us to improve our VO_2 max, lactate threshold, and running economy we needed to work at higher intensities, then why were we persisting with some moderate intensity work? Some obvious answers came readily, in that my thought process was focussed on marathon training, and specific marathon intensity lay in the moderate/threshold intensity zone, so this could partly explain some of my concern. Most studies were not that specific as to training for a particular event. My observation was, however, that pyramidal training was dominant across a range of distances that fell outside the threshold intensity zone, so I was still confused somewhat. The training group that we studied, ultimately, performed training which satisfied my bias.

Interestingly my supervisors came from a quite different background. Both performed training which had more intensity than I, in terms of volume and the actual level of intensity, so they found the training of the studied group interesting for the complete opposite reason. It was contrary to what they had grown up doing and learning about. Ultimately, what this segue into the personal motivation for the research reinforces, is that it seemed on the surface that consensus has not been reached on optimisation of training for distance running, nor the use and application of physiological profiling- answering 2 of the questions posed above, about what parts of sports science were and were not applied practically by the worlds' best athletes. It left unanswered, however, why. My ambition therefore, with this thesis, is to present how a group of world class athletes train, and in doing so demonstrate how this is in contradiction to recent conclusions within this field regarding the organisation of training. Moreover, I will show that the use of physiological zones to describe or organise training for endurance running may not always reflect practice and that some of the reasons for this may well be empirical, but at least some of it is because the contradictions identified stray so far from a practice base built on many years of history as described. I have suggested the additional use of zones based on a percentage of race pace as an alternative, and applied this in the papers we have published, resulting in a more consistent description of training for athletes of different event subspecialties. Interestingly, while we were working on these papers Bellinger *et al* published research demonstrating that using different physiological methods to analyse training (e.g. VT1/VT2 *vs*. LT1/LT2) results in the same training being described differently. The hope, on our behalf, was that perhaps factoring in race-pace based targets in a scientific manner might provide a further layer of nuance to prospective studies, and reflect the reality of what is going on. In this way, perhaps mistakes being made practically might be identified more readily, and allow for the more practical use of what we know about affecting physiological determinants of running performance.

In order to make this case 3 papers were planned. The first was this systematic review of the literature available on TID for endurance running, and the introduction of the notion of analysing training based on race-pace zones. Following this we analysed the training of our studied group, at group level, across middle- and long-distance subspecialties, comparing race-pace based zones and physiological zones to demonstrate how the analysis method affects the description of training, as all athletes within the group performed training which was very similar. Finally, we analysed the training of the leading athlete in the group over a period of 12 months, comparing race-pace based and physiological zones. In essence we simply analysed the training based on the coach's intention when planning, as pace and physiology are both considerations for him. So, our findings may be well-known to practicing coaches. The comparison of methods, however, allows for readier identification of where differences in the description of TID based on different methods manifest, and then potentially why success or failure may occur, on review.

3.1 Summary of Aims

- Examine the literature regarding optimal TID and periodisation for endurance running. (Publication 1)
- Introduce the concept of a performance related means to consider TID: race-pace based training. (Publication 1)
- Examine the actual training of an elite group international endurance runners. (Publication 2)
- Compare the training of the elite group to what was proposed by the literature via traditional analysis and our proposed analysis. (Publication 2)
- Present a case study on the employment of this method by a world-class athlete, continuing to compare the proposed method of analysis to traditional method. (Publication 3)
- Explore reasons why any potential discrepancies occurred. (All Publications)

3.2 Specific Aims by Publication

3.2.2 <u>Publication 1:</u> The Effect of Periodisation and Training Intensity Distribution on Middle and Long-Distance Running Performance: A Systematic Review

This paper was intended to highlight the issue as seen, and to introduce the concept of race-pace based zones. As described above the training for endurance events involves manipulation of intensity, duration and frequency of training sessions[32] but the precise detail of this "manipulation", however, remains an area of debate across the literature. To further guide understanding of this area, different training intensity zones have been described[32,57], determined by either physiological factors: i.e. lactate threshold (LT), ventilatory thresholds (VT), percentage of the maximum oxygen uptake (%$\dot{V}O_{2max}$), percentage of the maximum heart rate (%HR) or subjective factors: i.e. session goal or session rate of perceived exertion (RPE-Borg Scale). Three training intensity zones of endurance athletes are most commonly used in the literature, and are considered similar regardless of the method used to determine them. However, up to seven can be also used to describe the Training Intensity Distribution (TID)[18]. Both TID and periodisation of training volume and intensity are traditionally considered to be important factors in the design of a training program for endurance running performance.[75]

There appears to be longstanding consensus in the literature regarding factors that limit such performance, namely vVO_{2max},[8] $\dot{V}O_{2max}$,[5] LT[5,6] and running economy[7], and on how these factors could be improved by using different training intensity procedures. However, a disparate number of TIDs are employed in practice[76]. Three primary TIDs are recognised in this review; (1) the traditional Pyramidal approach, in which decreasing volume of running is performed in zones 1, 2 and 3 respectively. Typically[17] this has been described as comprising 80% in Zone 1, with the remaining 20% split between zones 2 and 3, decreasing respectively; (2) Polarised Training, in which relatively high volumes of training are performed in zone 1(~80%) and zone 3 (20%), with little or none in zone 2 and (3) Threshold Training, in which higher volumes (>20%) of running are performed in zone 2 than other models[17]. Previous research has identified pyramidal training as the primary TID employed by well-trained and elite endurance athletes, noting that "some world-class athletes adopt a so-called 'polarised' TID during certain phases of the season ".[36,57]

This observation has been supported by an observational review detailing the training of international level distance runners[19], which notes the emphasis on relatively high volume-low intensity in the training of athletes specialising in distances from 1500m to marathon. However, a training manual published by the International Athletics Federation (IAAF) based on the work of Renato Canova (the coach of some of the fastest Kenyan marathon runners in recent times, including World Record holders) has demonstrated a tendency towards a threshold-oriented TID[37]. Seiler & Tonnessen[32] argue the case for an 80:20 distribution ratio between high-intensity and low-intensity work based on observational reports describing the training of elite endurance athletes. These authors recognise both pyramidal and polarised models of TID as being most common in these athletes.

This apparent contradiction, thus, forms the foundation for this review of the literature on endurance running, and subsequently to analyse the available data where possible, by determining intensity zones relative to the goal race pace in different distances, rather than physiological or subjective variables.

3.2.3 <u>Publication 2:</u> Training Intensity Distribution analysis by Race Pace *vs.* Physiological approach in World-Class middle- and long-distance runners

This paper followed on from the demonstrated contradictions in paper 1 to present the training of a group of elite and world-class distance runner over 50 weeks, and to analyse it using 2 different approaches: 1) based on specific individual specific race pace and 2) based on physiological parameters. Analysed training data included training volume, intensity and frequency. In addition to the contradictions noted above, some further studies added to the ambiguity in this area.

A meta-analysis by Rosenblat et al[77] focussed on comparing the effect of polarised *vs.* threshold training on endurance sport performance. They concluded that polarised training produced significantly greater improvements in time trial performance and suggested that coaches should consider using polarised training to optimise endurance training and performance. However, this suggestion contrasts with the training practices of some elite level endurance runners-as noted in our paper above. Recent work by Casado *et al*[23,39] showed that the training of elite distance runners is actually characterised by large volumes in the *threshold* zone. Traditionally this pace would be considered to fall into Z2 physiologically. It should, however, be noted that in these studies, the authors did not specifically consider physiological zones when analysing the training data, as they sought to examine whether "deliberate practice" characterised training of elite runners, and as such, physiological zones were not needed as a reference.

Bellinger *et al*[4] added further to this potential conflict, in a study in which they compared 3 different methods of analysis of TID; by running pace, heart rate and rating of perceived exertion (RPE). Three zones were used in this study, and the times spent in Z2 and Z3 significantly differed depending on the method of analysis used. In this instance, running speed-based analysis suggested that a polarised distribution was being employed, whereas heart rate-based analysis suggested a pyramidal distribution of the same training. Recent work[23,47,56,78] which has focussed on the effectiveness of endurance training both in intensity distribution and periodisation has examined either change in physiological/metabolic parameters or time trial performance as a main outcome rather than actual competition or race performance. Thus, the contention is that this difference may lead to differing interpretations of how to optimise training.

It is against this background that this article aimed to analyse the training of a group of world-class athletes over a 12-month period, using an approach in which their training was organised into zones based on individual event specific race pace/performance, and to describe how such training was periodised over the course of the season. This is presented against the same training organised into the traditional physiological zones, based on testing done at the start of their season. We felt that proof of improvement of physiological parameters or time trial performance within a defined timeframe, when assessed independent of each other and of concurrent race performance, is not consistent with preparing for endurance running at an elite level, where race performance is the primary targeted outcome, and where longitudinal development and improvement is sought.

3.2.4 <u>Publication 3:</u> Training Characteristics of a World Championship 5000m finalist, and multiple continental record holder over the year leading to a World Championship final

After the results of article 2, we felt that there was evidence of a TID zone creation based on race-pace, albeit subconsciously, by elite coaches. To further elucidate this point, our 3rd paper was a longitudinal case study of a world-class middle and long-distance runner. It was proposed that this "Race-Pace" (RP) based approach to training is relatively common at the elite level. In this context, this case study presents 52 weeks of training of an athlete leading to the final of the World Championship 5000m in Doha 2019. The aims of this study were to: 1) Examine 52 weeks of training through a combination of training intensity distribution (TID) quantification methods such as physiological and race-pace based approaches, and 2) To identify possible relationships between physiological and training characteristics in this world-class runner.

4

RESULTS & DISCUSSION

'The outcome of any serious research can only be to make two questions grow where only one grew before''
Thorstein Veblen

4 Results and Discussion

4.1 Results Publication 1

4.1.2 Studies Selected

The search strategy yielded 493 total citations as presented in Figure 1. After removing 163 duplicates and reviewing the resultant 330 full-text articles, 16 studies met the inclusion criteria. Excluded studies had at least one of the following characteristics: participants were not middle- or long-distance runners, intervention/observation period lasted less than 4 weeks. The overall sample included 6 observational reports, 3 case studies and 6 interventions. 1 review was also included (Table 5).

4.1.3 Level of Evidence and Quality of the Studies

Four of the 16 included studies had a level of evidence 1c (high-quality RCT). The 12 remaining studies had a level of evidence of 2c or less as participants were not randomly allocated into the intervention or control groups. Also, mean score in the PEDro scale was 3.75 ± 1.9, with values ranging from 1 to 6

4.1.4 Characteristics of the Participants

Participants were characterised as recreational or high-level athletes, with delineation defined by whether the athletes competed internationally. A summary of participants' characteristics is presented in Table 6. The total number of participants was 215 (194 men and 21 women) with an age ranging from 17 to 51 years.

Table 6. Characteristics of the studies and participants*.

	Participants			Study Design	
Study	Number (M/F)	Age	Level	Randomised	Main Outcome
Robinson (1991)	13 (13/0)	26.1 ± 4.7	Elite	No	TID
Billat *et al* (2001)	20 (10/10)	Not specified	Elite	No	Physiological characteristics
Billat *et al* (2003)	20 (13/7)	Not specified	Elite	No	TID
Esteve-Lanao *et al* (2005)	8 (8/0)	23 ± 2	Well-trained	No	TID
Esteve-Lanao *et al* (2007)	20 (20/0)	27 ± 2	Well-trained	Yes	Race Performance
Tjelta & Enoksen (2010)	4 (4/0)	17.8 ± 1	Elite	No	TID & Race Performance
Enoksen *et al* (2011)	6 (3/3)	Not specified	Elite	No	TID & Race Performance
Stellingwerff (2012)	3 (3/0)	28.3 ± 2.3	Elite	No	TID
Ingham *et al* (2012)	1 (1/0)	26	Elite	No	TID & Race Performance
Tjelta (2013)	1 (1/0)	20-21	Elite	No	TID & Race Performance
Stoggl & Sperlich (2014)	21 (not specified)	31 ± 6	Well-trained	Yes	Physiological characteristics
Muñoz *et al* (2014)	30 (not specified)	34 ± 9	Recreational	Yes	Race Performance
Tjelta *et al* (2014)	1 (0/1)	25/26	Elite	No	TID
Clemente-Suarez & Gonzalez-Rave (2014)	30 (30/0)	Not specified	Well-trained	Yes	Aerobic Performance
Manzi *et al* (2015)	7 (7/0)	36.5 ± 3.8	Recreational	No	TID & Race Performance
Clemente-Suarez *et al* (2016)	30 (30/0)	Not specified	Recreational	Yes	Physiology & performance
Tjelta (2016)	129	Not specified	Elite	No	TID

*M/F = male/female; TID, training intensity distribution

4.1.5 Evidence for a Pyramidal TID

Four interventional studies exist which support the use of a pyramidal TID; Esteve-Lanao *et al*[47], Clemente-Suarez & Gonzalez-Rave[79], Manzi *et al*[80], and Clemente-Suárez *et al*[78]. Similarly, 4 observational reports[18,21,81,82] and 2 case studies[22,83] confirm the use of pyramidal training in elite and well-trained runners

Esteve-Lanao *et al*[47] examined the effect of decreasing volume of training performed at threshold intensity on running performance in 12 male sub-elite endurance runners, while maintaining equal volumes of high-intensity work between 2 groups (Threshold & Pyramidal training groups; Figure 2). Running performance was assessed by a simulated 10.4-km XC race assessed before and after the 5-month intervention period. The *Pyramidal* group displayed a significantly better improvement in performance than the *Threshold* group. The TID in both *Threshold* (Figure 2A) and *Pyramidal* groups (Figure 2B) was different from a race-pace based TID (Figure 2; ES>2.0, very large effect). It should be noted that zone 3 can only be considered a sub-set of Zone 2 in this analysis as details of the zone 3 training are not provided but are equal between groups.

Clemente-Suarez and Gonzalez-Rave[79], examined the effect of applying a pyramidal TID over a 4-week time period to 30 recreational athletes. One group (*constant*) maintained a constant weekly training load in terms of volume and intensity, while another group had an increasing proportion of higher intensity work, week by week over the 4 weeks. A final group were free to train as they wished. Total training volume for the 4 weeks was recorded by time (minutes). The constant group completed 1051(±11) minutes, the increasing group completed 1105(±1.3) minutes and the free group completed 1512(±67.6) minutes. The stated goal of the 4-week time period was to develop "aerobic endurance". No race distance or performance was specified, rather the changes were measured via laboratory testing. No significant performance differences existed between groups post-study, although the groups did exhibit different physiological changes over the 4 weeks. Clemente-Suarez *et al*[19], using data from the aforementioned study, found that the group with increasing intensity over the 4 weeks had a significantly better running velocity at 8 $mmol \cdot L^{-1}$ at mid- and post-condition. No time-trial or race performance data for the groups were provided so it was not possible to examine the TIDs in this method.

Manzi *et al*[80] assessed the TID of 7 recreational marathon runners in the preparation phase of a marathon training cycle. Interestingly, when their training (which was pyramidal in nature according to their baseline physiological testing) was assessed against their eventual race pace, it appeared to be a polarised type TID (Figure 3; ES>2.0, very large effect).

Robinson *et al*[81] analysed 13 national ranked male New Zealand distance runners' training during the "build-up" phase of their season and identified 2 training zones according to blood lactacte: above LT (4 $mmol \cdot L^{-1}$) or below LT. Training during this period was described as 96% below LT and 4% above LT.

Tjelta and Enoksen[21] described the training of a group of 4 top-level male Junior cross-country (XC) runners over the course of a season. Five training zones based on HR and blood lactate were used to describe the TID and training was divided into 3 seasons; Base, Track and XC. The training in this study can be described as traditionally pyramidal in distribution, with 78%, 81%, and 78% of the training volume having been carried out in the low-intensity zone 1 in Base, Track and XC seasons, respectively. Race intensity for these athletes across the whole season was zone 3 (10-km and 3-km), with some zone 4 (1500 m) races during the Track season. Training intensification (training phases closer to competition) is characterised by an increase in the volume just below, up to and over race pace (zones 3 and 4). In this study, when TID was calculated according to race pace, the volume of training performed above race pace was similar to other studies using either pyramidal or polarised methods[18,22,59,80].

Enoksen *et al*[18] analysed 6 top international Norwegian marathon and track distance runners' training in a subsequent study. 7 training zones were identified and used the determine TIDs. The marathon runners performed a relatively high proportion of their training at zone 2 (equivalent of marathon pace) and zone 4 (10-km pace) in their Base and Pre-competition phase with nothing at zone 3 (half-marathon pace), and then in competition phase, nothing at zone 4 and an increase in the volume at zone 3, while maintaining a relatively high proportion at zone 2. The track runners (who competed over 5-km) completed relatively high volumes at zones 2 and 3 in all phases. However, the volume in zone 3 dropped in the competition phase and zone 5 (3-km and 5-km race pace) volume increased. They had minimal volume in zone 4 (10-km pace) across all phases.

Esteve-Lanao *et al*[82] described the training of 8 regional and National class Spanish runners, using 3 intensity zones; up to VT_1, between VT_1 and VT_2, and above VT_2, and similarly described a pyramidal distribution (71% in zone 1, 21% in zone 2, 8% in zone 3).

Tjelta[83] analysed the training of the 2012 European 1500m champion over 4 years, and noted a pyramidal distribution over the time period, at all times of the season despite some variation corresponding to the periodisation of the athletes training. Five intensity zones were described relative to blood lactate, $\%HR_{max}$, and intended physiological adaptation, and during all phases of training the maintenance of a relatively high volume in zone 2 (threshold training) was observed. This does reduce closer to competitive season but still constitutes a larger proportion of training than zone 3, 4, or 5 at all time-points.

Similarly, the training of 9 times New York marathon winner Grete Waitz was also reported as pyramidal at all time points across a 2-year time period[24]. The periodisation identified 7 intensity zones and a decreasing volume of work done at increasing intensity levels was observed.

4.1.6 Evidence for a Polarised Training Intensity Distribution

Two interventional studies exist which support the use of a polarised TID: Muñoz *et al*[48], and Stoggl & Sperlich[84]. Both studies defined 3 intensity zones relative to physiological characteristics. Similarly, 3 observational reports[58,59,85] and 1 case study[86] confirm the use of polarised training in elite, well-trained and recreational athletes.

Muñoz *et al*[48] quantified the impact of TID on 10-km race performance in 30 recreational athletes. Two groups, emphasising polarised or threshold type training were examined. Both groups improved over a 10-week intervention period; although the *Polarised* group exhibited a better improvement over 10-km race distance than the *Threshold* group (5.0% *vs.* 3.6%, non-significant). Both groups completed an 8-week standard training program prior to the study, which was pyramidal in TID. In this study, both groups spent the same absolute amount of time in zone 3 with the polarised group zone 1 (Figure 4A) and the threshold group emphasising zone 2 (Figure 4B). The actual completed training of the polarised group was not a truly polarised TID as the authors intended that this group would complete only 5.0% of the training in Zone 2, rather than the 13.5% finally completed. The TID in both *Polarised* (Figure 4A) and *Threshold* groups (Figure 4B) was different from a race-pace based TID (Figure 4; ES>2.0, very large effect).

Stoggl & Sperlich[84] examined 48 athletes, 21 of whom were national-level runners, in their RCT comparing 4 different TIDs over a 9-week period. The TIDs were: High-Volume, Threshold, High Intensity Interval Training and Polarised. Polarised training resulted in the greatest improvement of the variables examined (VO_{2max}, peak velocity and time to exhaustion on a ramp protocol). A time-trial or race performance was not performed to allow analysis of race-pace zones based on this.

Billat *et al*[58] compared top class male Portuguese and French marathon runners to their "high-level" counterparts (as defined by a marathon time of 2:12). They described high-volumes of polarised training. Their zones were defined, however, by marathon race pace. zone 1 was described as <marathon pace (MP), zone 2 = MP, zone 3 >MP, a definition not replicated anywhere else in the literature and no specification of the tolerance around marathon pace for each zone is provided. The same authors also described the training of Kenyan distance runners (10-km specialists), and described 2 main TID types[59] : high-volume low-intensity and low-volume high-intensity. In the group studied there were 13 males (6 high-intensity type and 7 low-intensity type) and 7 females (6 high-intensity type and 1 high-intensity type). The lower volume athletes in this study tended to perform more of their training in zones 4 and 5 (4.3 and 5.0% respectively) than their high-volume counterparts, who only performed 1.4% of their volume in zones 4 and 5 combined, with 14.4% in zone 3.

Stellingwerff[85] described the training of 3 Canadian international marathon runners over a 16-week period before a marathon race. The intensity zones were defined subjectively by RPE as: zone 1 (easy to somewhat hard); zone 2 ("Threshold"); and zone 3 (very hard to maximal). A polarised distribution was described in which 74%, 11% and 15% of training sessions were performed in Zones 1, 2, and 3, respectively.

Ingham[86] presented the case study of an international 1500m runner, who improved his personal best from 3:38.9 to 3:32.4 over a 2 two-
year period. The analysis of his training showed a reduction in training volume performed between 80-90% $\dot{V}O_{2max}$ from 42% to 20% and between 90-100% from 20 to 10%. At the same time, low-intensity training volume (<80% $\dot{V}O_{2max}$ increased from 20% to 55% and training volume at 100-130% $\dot{V}O_{2max}$ increased from 7% to 10%, thus emphasising a shift towards a more polarised TID. Note that these numbers are approximate as the information is only provided graphically in the article, and that 1500m race falls at approximately 110% $\dot{V}O_{2max}$.

4.2 Discussion Publication 1

According to the results of this review, there is a clear dichotomous evidence base with regard to TID in the literature. The overwhelming evidence describes 2 main strands: Pyramidal and Polarised training.

Contemporary endurance training has developed, from a historical perspective from coaches such as Arthur Lydiard, who used pyramidal TIDs to coach successful athletes[19]. The more recent m1ove towards Polarised type TIDs has emerged as scientific evaluation of endurance performance has identified key determinants of endurance performance, and methods by which to improve these determinants[87]. However, the precise nature of the interaction of these determinants and the effect of that interaction remains elusive.

For example, although LT is recognised as one of the key determinants of endurance performance[6], threshold type training is considered to be more demanding than other TIDs (i.e. pyramidal and polarised), potentially because of effects on the autonomic and endocrine systems, or on the lactate/power profile[48]. When threshold training has been compared in this regard in the literature, it consistently proves to be less effective in the studies available. Yet, there is anecdotal evidence, at the very highest level, of the use of threshold training to great effect in structuring world best marathon performance.

The coach of a number of world class Kenyan athletes has written a marathon training manual for the International Athletics Federation (IAAF)[37], and has made publicly available the training programmes of his athletes. These programmes repeatedly show the use of high volumes (i.e. differing from the traditional 80:20 approach) of training in the threshold zone (as defined by $\%\dot{V}O_{2max}$, assuming 100% of $\dot{V}O_{2max}$ corresponds to approximately 3000m pace). The coach (Renato Canova) describes this training as specific race pace.

The periodisation employed, however, demonstrates an initial block of polarised training, emphasising high and low intensity, leading into a specific preparatory phase, which is threshold-oriented, thereby employing both of the main TIDs described at different phases of training, according to the intended goal of the phase. So, in the specific example, marathon pace lies in the threshold zone, so a relatively large volume of training is performed in this physiological zone as the date of a specific race approaches. The volume of training performed around race pace seems to be dictated by the distance of the impending race, with shorter races, requiring faster paces, seeing less volume, and longer races requiring increasing volumes in around race pace.

Thus, the dichotomous approach described above may be flawed in its inception. It may prove more valuable in future studies to examine the precise physiological characteristics associated with optimal race performance, and how these physiological characteristics change with different TID approaches. Similarly, different approaches may prove valuable at different phases and for approaching different races[48]. In this way, the training may be designed in the early parts according to physiological characteristics such as HR or lactate profile, but as the race date approaches, becomes more pragmatic and focuses on running at and around specific race pace, regardless of what is happening to physiological measurables[21,24]. This represents a way of incorporating the scientific principles which are fairly well established as being important for specific race distance performance, while also being cognisant of the fact that the literature is deficient in describing an optimal TID and periodisation strategy, based on good evidence[19].

It is well established that from races as short as 1500m, the aerobic system is the main contributor of energy (85%)[88] so the TIDs seen reflect that, as no matter what TID is examined zone 1 is always the highest proportion. However, when comparing physiological-based intensity zones and race pace-based intensity zones it seems from the data assessed in this review that race pace may be a larger factor in the design of training programmes than physiological variables. This may be a coaching flaw, but the interesting similarity in the TIDs when analysed by a race pace-based approach at least warrants some attention as these are data from successful athletes. As discussed above, no optimal TID has been well established, and similarly no optimal numbers for the physiological determinants (vVO_{2max}, $\dot{V}O_{2max}$, running economy and LT) of middle and long distance running to predict performance exist[2]. The interaction between these variables is the key to endurance running and it may be possible that race pace-based training provides the perfect stimulus for their concurrent development. As already described above, training aimed at improving threshold seems to limit the development of $\dot{V}O_{2max}$[84]. However, as Coyle & Krauenbuhl[5] showed, large variation in laboratory endurance performance is explained by the %$\dot{V}O_{2max}$ which can be maintained at threshold so this limitation may not be a hindrance to performance. The specificity of intention may be more important.

Race pace-based zones may also reflect the fact that races in endurance running competition are directly comparable because of the similarity of courses and the validity of time comparison on different courses. Other endurance sports, such as road cycling, rowing or XC skiing, which have been examined in the literature on TID[17,89] do not share this same capacity for direct competition to competition comparison of speed, because of the nature of different courses characteristics (i.e. profile, altitude...). Training organised, therefore, based on physiological characteristics for these sports is the norm. No study in these sports, to the authors' best knowledge, has reported a polarised TID based on zones that are externally defined (i.e. power or speed).

This dichotomy between measuring and monitoring workload internally (physiologically guided) *vs*. externally (e.g. pace guided) has been explored in 2 recent reviews: Foster *et al*[90] and Mujika[87]. Foster *et al* outline the practical difficulties of accurately monitoring internal workload/physiological parameters, which they note are lessening. Nonetheless such practical difficulties should not affect the development of theoretical principles based on physiological measures (e.g. Running economy, $\dot{V}O_{2max}$ and LT) should an integrated approach to their concurrent development become evident.

Further studies looking at the behaviour of physiological characteristics such as HR response, top speed and lactate profile at different phases of a season, and also how they change, in the short and medium term in response to training are thus warranted. Comparison of these measures to race performance, along with physiological profiling compared to performance, may also allow better understanding of the interactions between physiological characteristics, and the impact of these interactions on performance. This may allow for better planning and prescription of training, which is founded on evidence rather than anecdote/tradition.

4.3 Results Publication 2

4.3.2 Participant characteristics

The descriptive characteristics, physiological variables and performance of the participants are presented in Table 7. The male middle-distance athletes achieved times (min:s) ranging 1:45.60-1:46.77 (800m) and 3:34.38-3:36.30 (1500m). The female middle-distance athletes achieved times ranging 2:00.24-2:04.89 (800m) and 4:04.93-4:10.42 (1500m). The male long-distance athletes achieved times ranging from 13:05.23-13:26.38 (5000m). The female long-distance athletes achieved times ranging from 15:06.67-15:18.91 (5000m).

Table 7. Performance and physiological characteristics of participants (Mean ±SD)

	Male (*n*=4)	**Female** (*n*=3)
Age (yrs)	**5.1** ± 2.5	27.5 ± 0.7
BW (kg)	66.2 ± 4.3	51.4 ± 3.3
VO_{2max} ($mL.kg^{-1}\cdot min^{-1}$)	73.8 ± 2.1	61.4 ± 4.2
vVO_{2max} ($km\cdot h^{-1}$)	22.1 ± 0.4	19.3 ± 1.1
LT1 ($km\cdot h^{-1}$)	17.9 ± 0.8	16.1 ± 0.1
LT2 ($km\cdot h^{-1}$)	19.7 ± 0.6	17.5 ± 0.07
RE ($mL\cdot kg^{-1}\cdot km^{-1}$)	191.9 ± 6.2	173.1 ± 17.1
Performance	1:46.04 – 1:46.77 (800m)	2:00 – 2:04 (800m)
	3:34.9 – 3:36.6 (1500m)	4:03 – 4:10 (1500m)
	13:05 – 13:36 (5000m)	15:06 – 15:18 (5000m)

BW, Body weight; VO_{2max}, Maximal Oxygen uptake; vVO_{2max}, Velocity at which Maximal Oxygen uptake is reached; LT1, Speed corresponding to the first lactate threshold; LT2, Speed corresponding to the second Lactate Threshold; RE, Running economy

4.3.3 Training volume and intensity distribution

The mean weekly volume for the group was 135.4 ± 29.4 $km\cdot week^{-1}$. Specifically, the long-distance athletes performed an averaged of 145.9 ± 27.9 $km\cdot week^{-1}$, whereas the middle-distance runners performed 127.4 ± 28.7 $km\cdot week^{-1}$. A sample week from General Preparation Phase 1 is shown in Table 8. The General Preparation Phase took place between October 2017 and January 2018, following a 2-week recovery phase.

Table 8. Sample Week from General Preparation Phase 1

	AM	PM
Monday	60 min easy running	30 min easy running + drills and 150m strides
Tuesday	8x1km (60s recovery). Run at current 10km race pace, with 5th and 7th reps run 10 seconds faster	30 min easy running
Wednesday	60 min easy running	30 min easy running
Thursday	9km "Threshold" run-determined by Heart Rate	30 min easy running
Friday	60 min easy running	
Saturday	6x800m Hills-pace subjective-5k "effort"	30 min easy running
Sunday	105 min easy running	

4.3.4 Comparison of training zones

Figures 2C and 2F display the comparison of zones via race-pace *vs*. physiological methods for the middle- and long-distance groups respectively. The middle-distance group (Figure 2C) showed no differences for Z1 by the two methods of analysis. There were moderate effect sizes for the differences between the two methods used to calculate Z2 (ES=0.63) and Z3 (ES=0.61), with Z2 greater by race-pace based analysis and Z3 greater by physiological analysis. The long-distance group (Figure 2F), showed no differences between the two methods of analysis for any zone.

As a group there was no difference between Z1 when calculated as race-pace based zones or using physiologically based zones. However, there was a large effect size (ES=1.20) for the difference between the two methods used to calculate Z2, and a moderate effect for the Z3 difference (ES=0.93).

4.3.5 TID across the season

Figure 2 also shows the training intensity distribution for the subgroups across the microcycles of the season. The approach based on race-pace zones produced pyramidal distributions for both groups across all phases of the season (Figure 2A and 2D). The physiological approach produced a more polarised type distribution in the middle-distance runners (i.e. more training performed in Z3 than Z2), with the General Prep phase the exception-showing a pyramidal distribution (Figure 2B and 2E). The long-distance subgroup was a more pyramidal type distribution on analysis using physiological zones across all phases of the season (Figure 2E). Significant differences in zones between approaches are noted only in the “Specific Prep 1” and “Competitive 2” phases in the middle-distance subgroup in Z2 (Figure 2A). The analysis by race pace returned higher values for this zone in these phases, effect sizes 0.93 (moderate) and 1.2 (large), respectively.

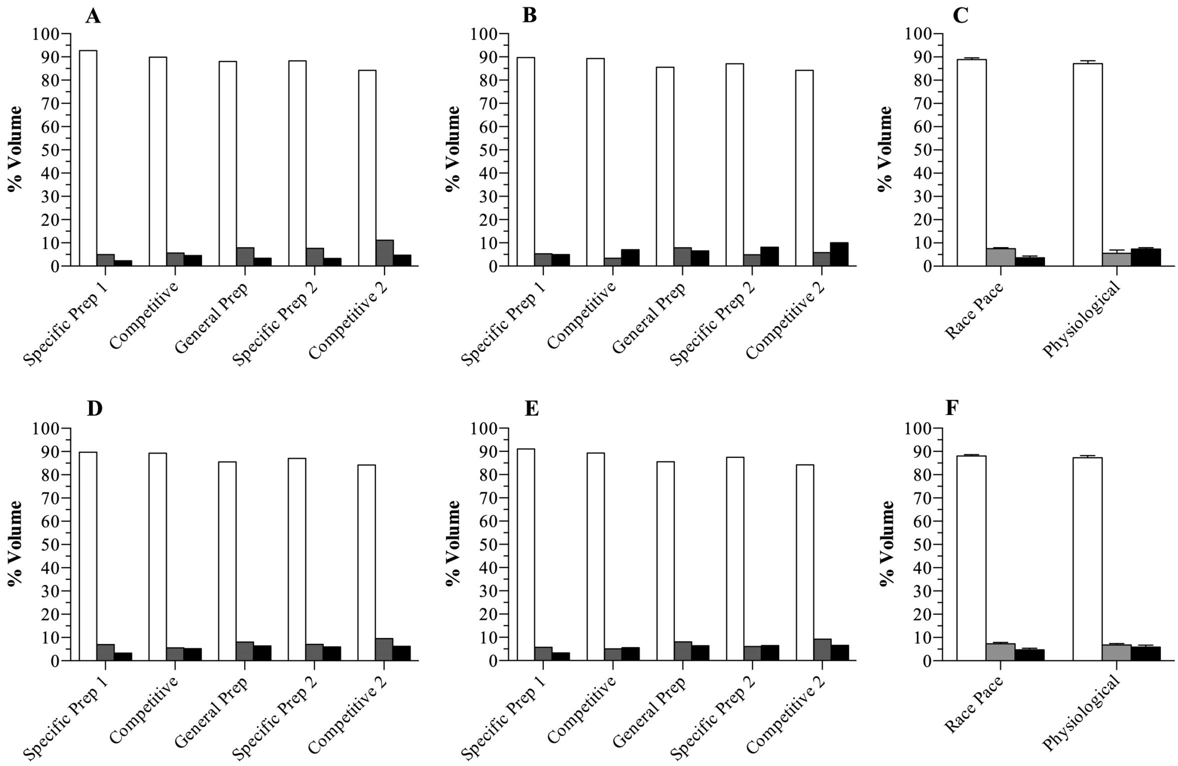


Figure 2. Training Intensity Distribution (TID) comparison. TID using a race-pace based approach in the middle-distance runners during the different phases of the athletic season (A), TID using a physiological approach in the middle-distance runners during the different phases of the season (B), TID comparison between a physiological and a race-pace based approach in the middle-distance runners over 50 weeks (C). TID using a race-pace based approach in the long-distance runners during the different phases of the season (D), TID using a physiological approach in the long-distance runners during the different phases of the season (E), TID comparison between a physiological and a race-pace based approach in the 5000/10000m runners over 50 weeks (F).

4.3.6 Race-pace and physiological method comparison

Figure 3 shows how the race-pace approach and the physiological approach interact when mean running volume (at a given velocity) is plotted against absolute running speed. The percentage volume is represented on a log scale, because the relative volume of training done at lower speeds is so much greater than at higher speeds. In the figure 16 $km \cdot h^{-1}$ represents volume of training done up to velocities of $16km.h^{-1}$. All other points represent the volume performed between the previous point and the relevant one (e.g. 17 $km \cdot h^{-1}$ represents training volume performed between 16 and 17 $km \cdot h^{-1}$).

It shows the middle-distance group (Figure 3A) with a narrower physiological Z2 velocity band than the long-distance group (Figure 3B), and shows at what points target race speeds are.

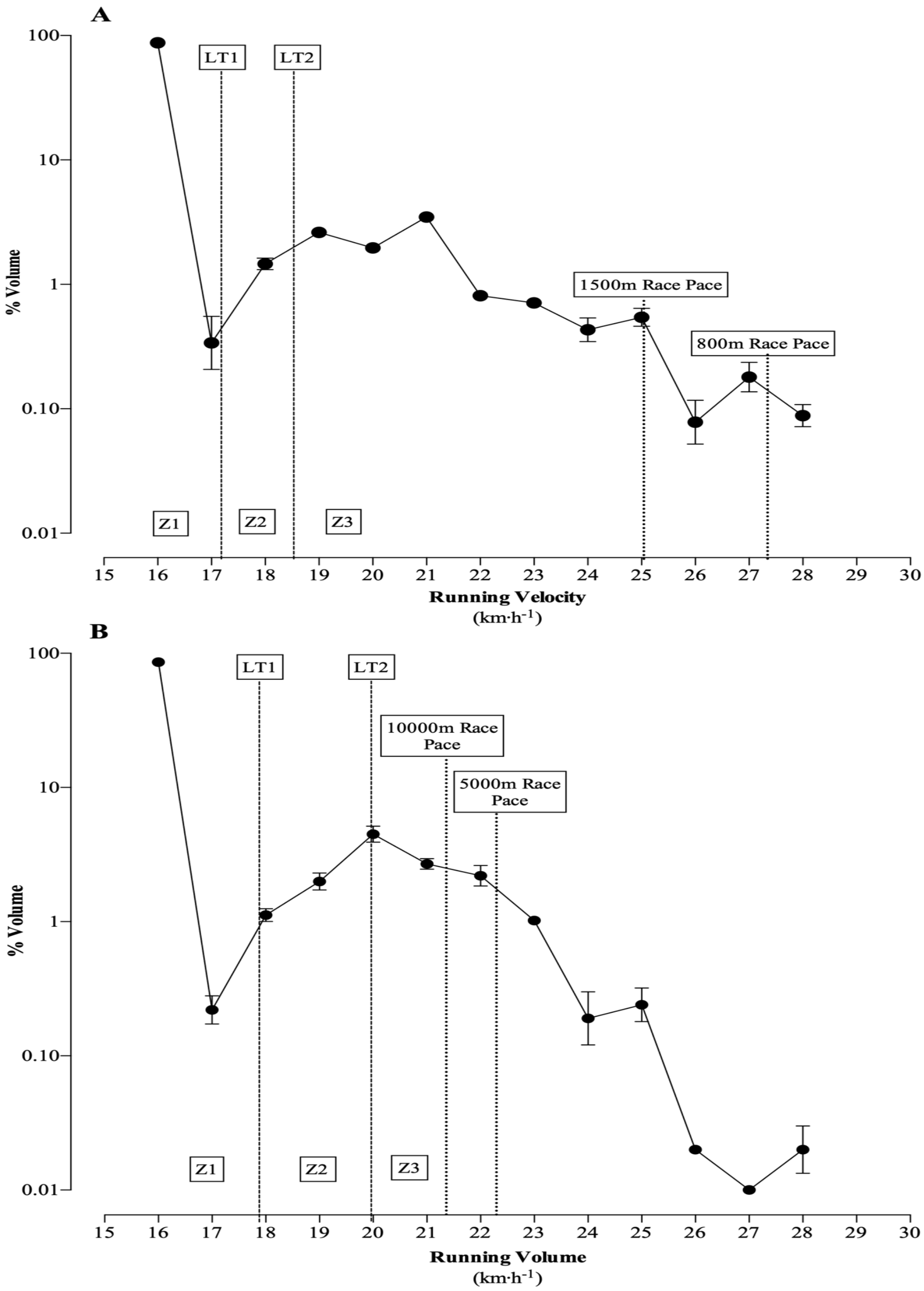


Figure 3. Training Volume (%) plotted against absolute speed over the 50 analysed weeks with physiological zone delineation and race-pace points included; in the 800/1500m runners (A), in the 5000m/10000m runners (B).

4.4 Discussion Publication 2

The main finding of this study was that the training intensity distribution of a group of world-class distance runners performed was more consistently linked to proportions of race-pace than physiological parameters. Given that the expressed main coaching intention for the group was the development of race pace, this is not a surprising finding. Figure 3 provides clarity to this point. The arbitrary percentages of race pace chosen for analysis have resulted in Z2 by race-pace approach spanning a much wider range than Z2 by physiological approach (~ 4 $km \cdot h^{-1}$ *vs.* 2 $km \cdot h^{-1}$), and therefore is less sensitive to changes in intensity distribution around these paces. Equally the opposite is true when Z3 is considered by physiological approach *vs*. race-pace based approach.

When viewed over the course of the different phases of a season, race-pace based analysis returned a consistent pyramidal TID. However, the TID was more variable -between pyramidal and polarised-when analysed via physiological parameters. Interestingly, the athletes performed a relatively high proportion of their training in Z2, consistent with recent studies[4,23]. This was true regardless of whether training was analysed physiologically or by race pace, although as noted above Z2 by race-pace approach included intensities well in excess of physiological "threshold". Nonetheless the current authors have also noted this use of training at threshold intensity in world-class distance runners, and feel that the race-pace based analysis at least links training analysis to coaching intention in a number of other elite training groups.

The volume of training done by the group in the current analysis is relatively consistent with what has been reported in recent literature on world class distance runners[19,20]. The slightly lower volumes seen may be explained by the fact that non-regular training weeks were not excluded from the total volume. The athletes showed peak weeks in excess of 160 km, which is entirely consistent with what has previously been reported in the studies aforementioned. Interestingly, close to 85-90% of this groups' total volume lies in Z1, regardless of method of analysis, which is higher than the traditionally proposed "80:20" rule[17]. This states that approximately 20% of total volume will be performed in higher intensity zones, with the remainder low intensity. The current findings, however, are consistent with Casado *et al*[23] finding that volume of easy running was the best predictor of race performance.

Z2 (*threshold* zone) has traditionally been the zone around which much of the debate has centred. Recent work has suggested that training in this zone is less effective than pyramidal or polarised training[77,84–86]. The results of this study demonstrate than an elite group of distance runners, who were successful during the time period study, used "threshold training". By physiological approach analysis the middle-distance runners in this group performed slightly more training in Z3 than Z2-although the difference was minimal. The long-distance athletes demonstrate a pyramidal approach (Figure 2B & 2E). This is despite the training being performed being virtually identical. The reason for this apparent contradiction lies in coaching intention and the differences between velocities at lactate threshold in the 2 sub-groups of athletes. The longer distance athletes tended to have higher velocities at lactate threshold, therefore training that lay just below the threshold in that group would lie just above the threshold in the middle-distance group i.e. Z3. However, training sessions at this intensity were often performed as a whole group-thereby creating the difference.

The analysis showed that when the training of this group of elite distance runners is considered relative to their individual target race-pace, a pyramidal type training intensity distribution is seen, regardless of phase of training (Figure 2C and 2F). This pyramidal distribution was also preserved across athletes competing at different race distances, ranging from 800m to 10000m. However, the absolute training intensities of this group were similar for athletes competing over different distances, and as a result, differences were seen in the volumes in respective relative zones. Longer distance athletes (5000/10000m) had more volume in their higher relative intensity zones than middle-distance athletes, although both demonstrated pyramidal distributions.

Conversely, analysis by physiological zones demonstrated a periodised type distribution in the middle-distance runners across 4 of the 5 phases of the season (Figure 2B), while the pyramidal nature of the long-distance athletes TID was preserved (Figure 2E). This reflects the fact that the longer distance athletes had higher velocities at lactate threshold than their shorter counterparts, so that their pace/speed threshold for "higher intensity" work occurred at greater speeds.

This dichotomy is highlighted very well in this study, as both groups performed virtually the same training-with the only variation arising in volume of easy/Z1 running. The more recent paradigm is to recommend polarised type training based on physiological parameters, whereby physiological testing, zone creation and training prescription feeds forward to race performance, which does not consider the variety of inputs outside the traditional metabolic considerations, which can affect endurance performance. Further to this, our contention is that a move away from "threshold" training, based on the recent studies above described, would be mistaken in its conception. This is because world class runners perform large proportions of their training in Z2[20,23,39], and because the physiological approach links performance to physiological parameters only, despite a failure in the literature to provide practical examples of where physiological characteristics can predict running performance. However, analysis by race-pace based approach alone is also imperfect using our current delineations, because Z2 spans a range of intensities which will provide very different training stimuli.

An alternative paradigm, which can incorporate metabolic, cardiopulmonary, neuromuscular and biomechanical factors is proposed. In this paradigm, race performance informs training prescription, as well as interpretation of physiological testing. We suggest the potential for allometric profiling of physiological parameters based on contemporaneous race performance, to attempt to create a "signature" physiological profile which corresponds with specific race performance. Such an approach recognises the multifactorial nature of the physiological components of distance running performance, and the potential "substitution effect" of individual parameters. This can also allow for non-physical factors such as psychology/motivation. This approach may mirror the approach of Sandford *et al*[91] in their concept of an Anaerobic Speed Reserve (ASR), in that they attempt to link external demands of race performance and physiological factors influencing middle-distance running. In this model, strictly limited to middle-distance (800/1500m) running performance, training is expressed relative to ASR, which is the difference between vVO_{2max} and maximal sprint speed.

The impact of the fact that this is a study involving elite athletes should also be considered. In elite runners, the difference between maximal sprint speed, vVO_2 max, vLT and low intensity running will naturally be far greater than in recreational or untrained individuals, given that elite is being defined by how fast they can run. Therefore, zone delineation is much more clear. In untrained and recreational runners, it is conceivable and probable that Z2, for example, represents such a narrow pace band that the difference in subjective intensity between it and Z3 is difficult to distinguish, potentially allowing for training mistakes. This may also highlight a potential weakness of using a polarised approach, as it will reduce the amount of specific training done for distances in duration of 40-60min. Interestingly, however, a recently published paper compared the effects of polarised and threshold training (described as focused endurance training) in 38 recreational runners over 8 weeks, and demonstrated similar improvements regardless of TID employed[91].

4.5 Results Publication 3

4.5.1 Performance

The athletes' seasons bests from 1500m to 10000m are illustrated in Table 9. The athlete raced 20 times in the 52 weeks analysed. He achieved personal bests-over 1500m and 10000m, the latter being a National Record. In addition, the athlete qualified for and competed in the 1500m and 5000m at the World Championships in Doha, Qatar in October 2019. He made the final of the 5000m, finishing 12th, and the semi-final of the 1500m. He is currently ranked 14th over 1500m and 5000m and 16th over 10000m, in the official World Athletics (WA) Rankings.

Table 9. Physiological, Performance and Sample Training characteristics of the participant

Characteristics	
Height	1.88 m
Weight	67 kg
$\dot{V}O_{2\ peak}$	73.5 mL·kg^{-1}·min^{-1}
Velocity at LT1	18.3 km·h^{-1}
Velocity at LT2	20.3 km·h^{-1}
Running Economy at LT1	193 mL·kg^{-1}·km^{-1}
Running Economy at LT2	198 mL·kg^{-1}·km^{-1}
1500m PB (achieved during period)	3:31.81
3000m SB/PB	7:38.22/7:34.79
5000m SB/PB	13:05.63/13:05.23
10000m PB (achieved during period)	27:23.80

PB, personal best; SB, season best; LT1, first lactate threshold; LT2, second lactate threshold

4.5.2 Training Summary

The athletes' training over the year relative to running speeds and physiological zones is displayed in Figure 4. Overall training volume is displayed in km ± SD in figure 2 for all time periods.

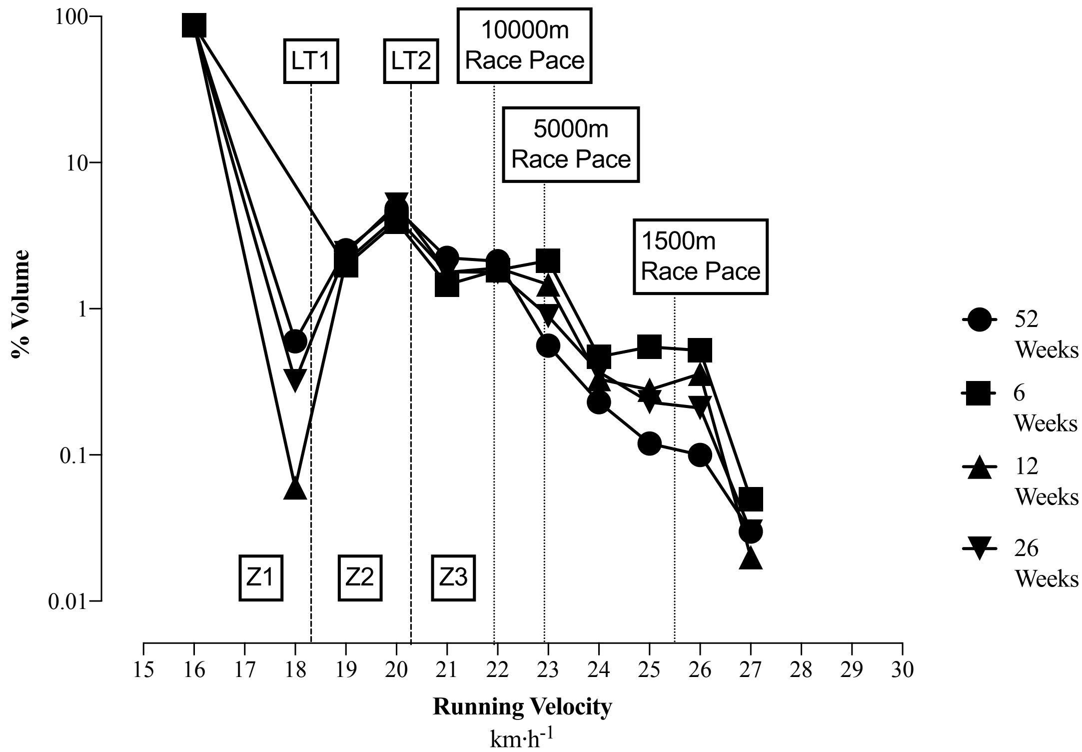


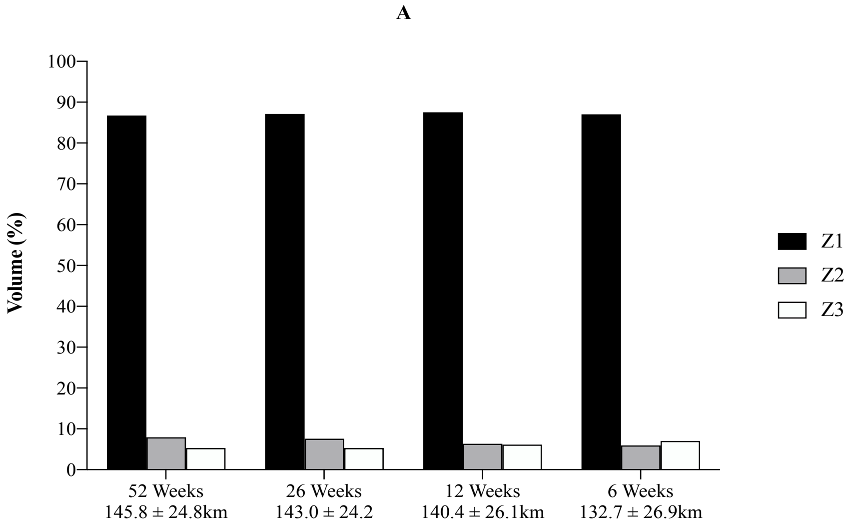
Figure 4. Training Volume (%) plotted against absolute speed over the last 6, 12, 26 and 52 analysed weeks with physiological zone delineation and race-pace points included.

4.5.3 Training Volume relative to physiological and race-pace zones

Figures 5A and 5B illustrate the overall volume and proportion of training done in each of the physiological, and race-pace zones, respectively, across the year. A pyramidal structure is seen in the physiological analysis of the 52, 26 and 12 weeks prior to the World Championships. The last 6 weeks, however, demonstrate a slightly polarised distribution. A pyramidal distribution is seen via RP analysis across all time periods.

4.5.4 Training Session types

The athlete performed 528 sessions over the course of the 52 weeks, including races. 392 sessions (74.2%) were classified as easy runs, 75 sessions (14.2%) were classified as continuous threshold (at a speed/intensity close to or at vLT) sessions and 7.8% (41) of sessions were interval sessions, with the remaining 3.8% representing races (20).



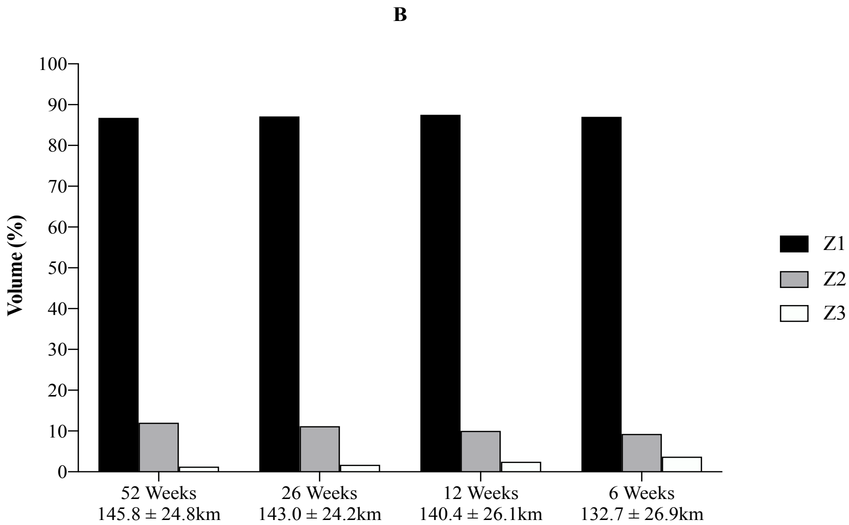


Figure 5. TID by physiological approach (A) and Race-Pace approach (B) over different periods of the studied year

4.6 Discussion Publication 3

The case study presents the training of a world class middle-distance runner over the course of a successful season. The volume of running observed over the course of the season is in line with previous work detailing elite training volumes[19]. The large volume of easy running is now a recurring feature across studies[18,23]. In this study TID changes across the season, relative to race pace and physiological zones. This clearly demonstrates an increasing specificity of work done around race pace as goal competition approaches (Figure 5B). A switch from pyramidal distribution to polarised distribution is seen in the last 6 weeks before goal competition, when physiological zones are considered (See Figure 5A).

In Jones *et al* very recent analysis of the sub 2-hour marathon attempt group, the authors reported comparable physiological values to the values for this athlete[29]. Both our subject and Jones' group had relatively modest $\dot{V}O_{2max}$ by elite endurance standards (73.5 *vs*. 71.0 ± 5.7 mL·kg·min^{-1}). Similar values between the subject and the group are also seen for velocities at LT1 and LT2 (18.3 *vs.* 18.9 ± 0.4 km·h^{-1} and 20.3 *vs.* 20.2 ± 0.6 km·h^{-1}). The athlete in this study demonstrated greatest difference to the group studied above in running economy sub-maximally and at 21 km·h^{-1} (193 *vs.* 189 ± 14 mL.kg^{-1}·km^{-1} and 199 *vs.* 188 ± 20 mL·kg^{-1}·km^{-1}). The training data provided by this case study demonstrates an insight into how this physiological profile seen may be attained. Further work, which relates elite performance to observed physiological profiles may allow for training to be informed more and more by physiological parameters in athletes such as these-to allow for more precise prescription and analysis of training.

This work has highlighted the fact that elite performance does not require exceptional physiological characteristics across all of the 3 mentioned above. What Jones *et al*' testing also showed is that the best athletes in the group were able to maintain approximately 96% of LT2 for marathon distance with very consistent running economies at increasing paces, an exceptional fractional utilisation of oxygen. Interestingly, the athlete in this case study displayed a similar metabolic profile to runners competing at significantly longer distances, with a difference in running economy noted. Whether this is common to world-class runners of shorter distances remains to be shown. It would also be useful in future work to include parameters such as maximal sprint speed, power, and reactive strength, to provide further clarity to profiles compatible with world-class performance at different distances.

As mentioned earlier, recent work has pointed towards a polarised approach being the most effective way of improving endurance performance[77]. The results of this study are at odds with this. However, this may be explained by a number of considerations. Firstly, we have focused solely on running-the weight bearing nature of running and technical, biomechanical and neuromuscular considerations associated with this may differentiate it from other sports. Secondly this athlete demonstrated a polarised training block for 6 weeks leading into competition. It seems to be the result of increasing specificity of training around paces relative to target performance in this athlete-per the coaches express intention. Indeed, some other studies have found this specific periodisation trend in elite distance runners, involving a switch from a more pyramidal TID during the preparatory and competitive periods to a more polarised TID during the competitive period[83]. Recognition of such patterns may be important. It would seem that success in endurance sport is the result of years of consistent training which includes high volumes easy running and continuous threshold run[23,39] . Therefore, studies that have identified a specific response to a training intervention, without considering prior training, may be flawed. Longer term studies observing physiological fluctuation, tracked against performance fluctuation, may provide further value.

5

GENERAL DISCUSSION

'The aim of argument, or discussion, should not be victory, but progress.'
Joseph Joubert

5 General Discussion

5.1 General Concepts

The observations above are likely not unexpected to many people. However, as mentioned already, this thesis was inspired by the fact that scientific research was directing us down a path already trodden in the 90's, whereby volume and moderate intensity were forsaken for higher intensity focused training. Admittedly, personal bias was a motivator, but certainly what is presented above is food for thought. It is not, however, the first-time race pace has been examined as a potential training intensity zone delineator. Muñoz and Seiler[36] investigated whether race pace represented a better option than traditional physiological based zones for peaking for performance. They noted similar outcomes in 10 km performance over their 6-week study, but with slightly different physiological adaptations between the 2 methods. Tonnessen *et al*[92] noted a tendency toward specificity in the peaking phase of Olympic gold medalists in cross-country skiing, both in terms of mode of training and the intensity of training. So, these 2 studies seem to be an example in the literature of acknowledgment of the tendency towards race pace or intensity as a practical factor in training design.

More overtly Jack Daniels wrote a training book[93], in which a large portion of the book is dedicated to linking race performance to training-although zones are not created, rather training paces. This is done through the creation of a concept called VDOT. This concept assigns a value to a race performance and builds the training paces from this value. Linking this to physiology is explained as follows:

"vVO_2max reflects the runners' economy and VO_{2max} and will be the same for all individuals of equal race ability-although one runner might accomplish his or her vVO_2max with great economy and a relatively meagre VO_{2max} and another runner with not-so-great economy and a high VO_{2max}"

There are some assumptions underpinning this statement which are absolute in their attitude to physiology. For example, while vVO_2max is a factor in endurance running performance[5] the assumption that a race performance can be used to state that people with similar performances will therefore have similar vVO_2max is not corroborated by any evidence, and so the basis for the tables is somewhat flawed. Nevertheless, these tables based on this assumption remain popular with coaches and athletes still.

So, we continue to go round in circles with this problem. Race performance seems to have an effect on programming, but an attempt to frame this above by Daniels in physiological terms is flawed. The complexity of the physiological response to endurance exercise may have a bearing on this. In a recent study[94] David Poole, along with (amongst others), one of the giants in exercise physiology in George Brooks, provided a review of the concept of anaerobic or lactate threshold. The authors of this paper prefer to delineate training intensity zones using the concept of critical speed or power, rather than thresholds based on lactate or ventilatory measure. The rationale is that critical speed or power represents a metabolic steady state, at which the body is maintaining a homeostasis of sorts. Their view that the precise mechanisms underpinning this are complex and changeable, likely give weight to the notion of an external guide, such as power or velocity, for training. The use of for example, the lactate or anaerobic threshold, to calculate zones, can be widely affected by the method used to calculate such a threshold mathematically-which has been shown to demonstrate significant variability, depending on the method used[95]. A concept which has attempted to link this complexity with external variables such as speed or power is critical speed or power.

5.2 Critical Speed

Critical speed, or power, is a concept first developed in the 1960s by Monod and Scherrer[96]. It recognizes a curvilinear relationship between running speed or power and duration of exercise. Mathematically, there exists a point at which running speed or power can be maintained indefinitely-this is known as the critical speed/power, and represents an ability to achieve a metabolic steady state[97]. Jones, Burnley and Vanhatalo have published extensively recently on this topic[38,98–103]. It is said to represent the threshold between heavy and severe exercise intensity[98] (Figure 6 adapted from Burnley and Jones).

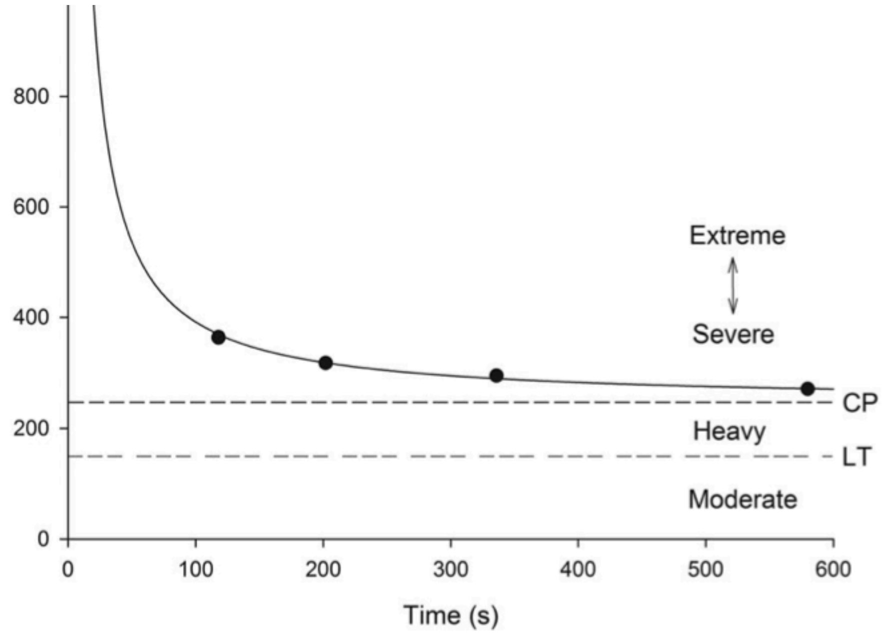


Figure 6. Graphical representation of Critical Speed/Power. Burnley and Jones[98]

Poole's study above[94], while questioning the concept of a lactate, or anaerobic threshold, suggest that the first rise in lactate during progressive exercise-traditionally described as the lactate threshold, may represent the separation of moderate from heavy exercise-as depicted in Fig 6. The other papers cited demonstrate that critical speed represents an intensity that is sustainable for approximately 30-40 minutes, and has been found to occur at intensities between 70 and 90% of $\dot{V}O_{2max}$[104]. It is not without its criticisms as a concept, however. The manner in which it is calculated can lead to variance[105,106], and a number of different approaches exist by which a critical speed/power profile can be calculated, ranging from multiple trials to exhaustion over varying durations to a single trial estimate [107,108]. A recent paper by Iannetta *et al*[109] attempted to reconcile the calculation of critical power and maximal lactate steady state, and to compare them to a maximal metabolic steady state. Although only one paper, it further highlights the fact that there are still methodological debates about these "thresholds" or points which are not present when considering race pace.

On the other hand, critical speed/power frameworks have recently been successfully used in the literature to analyse elite endurance events/performances[110]. In this paper Kirby *et al* analysed the 5000m and 10000m men's races at the 2017 World Championships. Using regression of the PB's over different distances of the athletes in the race they calculated the critical speeds of the athletes, and their D' (or finite amount work achievable above the critical speed), and were able to predict accurately finishing positions of the athletes, through a dynamic analysis based on lap by lap splits, considering the pace and activity in the race.

Pettitt[111] examined the potential use of critical speed in interval training prescription and in development of race strategy. A method of prescribing training to evoke similar metabolic responses by varying either duration or speed, based on critical speed and D' was described. This move towards describing training as simply provoking "similar metabolic responses" seems to represent a move away from the notion of training for specific physiological characteristics such as VO_{2max}/threshold etc.

More recently the "Critical Speed/Power" concept has been the subject of debate for a number of reasons.[112,113] These include methodological but also include theoretical foundational reasons such as the possibility of exercise for an "indefinite duration". Notwithstanding this debate the concept is an attempt to integrate physiology with performance factors, and warrants mention in this thesis.

5.3 Other Perspectives on a Race-Pace *vs.* Physiological approach to Training

Critical speed, or power is an alternative approach to the 2 which form the basis of this thesis, i.e. physiological vs race-pace driven training, and may represent a method to link physiology to performance satisfactorily, albeit with some outstanding methodological questions. There are also other published opinions and approaches to address this problem, as well as support and criticism for the use of race-pace as a guide to training.

In a superb recent interventional study Filipas *et al*[114] studied a group of well-trained endurance runners over 16 weeks, creating 4 groups. They alternated the training intensity distribution in 2 groups, switching from a pyramidal to polarised TID after 8 weeks, and vice versa in another group. In 2 more groups they maintained polarised or pyramidal training throughout the 16 weeks. Training load was kept constant in all groups. The group which changed from a pyramidal to a polarised distribution had larger improvement in 5km time-trial performance than the other 3 groups. The authors noted that this reflected practice in elite endurance running, and this is consistent with the papers we have presented above. The authors of this paper used physiologically delineated zones, but the switch from pyramidal to polarised reflects common practice of working closer to race-pace later in a cycle.

As we have discussed above, whether this type of practice is more suited to running than other types of endurance sport for a number of reasons, including consistency of terrain (i.e. track/road) remains to be seen. A recent example,[115] in kayaking, however, points out some issues. They noted differences in training intensity quantification, depending on the method used, as we have discussed[4]. They noted a very low inter-individual difference for intensity quantification using race-pace. This was largely attributed to the fact that zone 2 via race-pace approach had a wider speed range than other methods. This agrees with our findings, and they point out, makes questionable the assertion that race pace approach is favourable. What should be noted is that the markers for zone delineation in our work have been arbitrarily selected up to this point. In the future, more selective reasoning for the creation of zones by this approach would be preferred. Secondly, if as is argued above by Poole *et al*[94], the concept of lactate or anaerobic thresholds are incorrect then the physiological basis for zone creation is undermined. It may well be argued, at that point, that actually training for performance reflects a task-specific process, and that the intensity distribution represents preparation, physically but also in other ways, for the task at hand. This will be discussed further later.

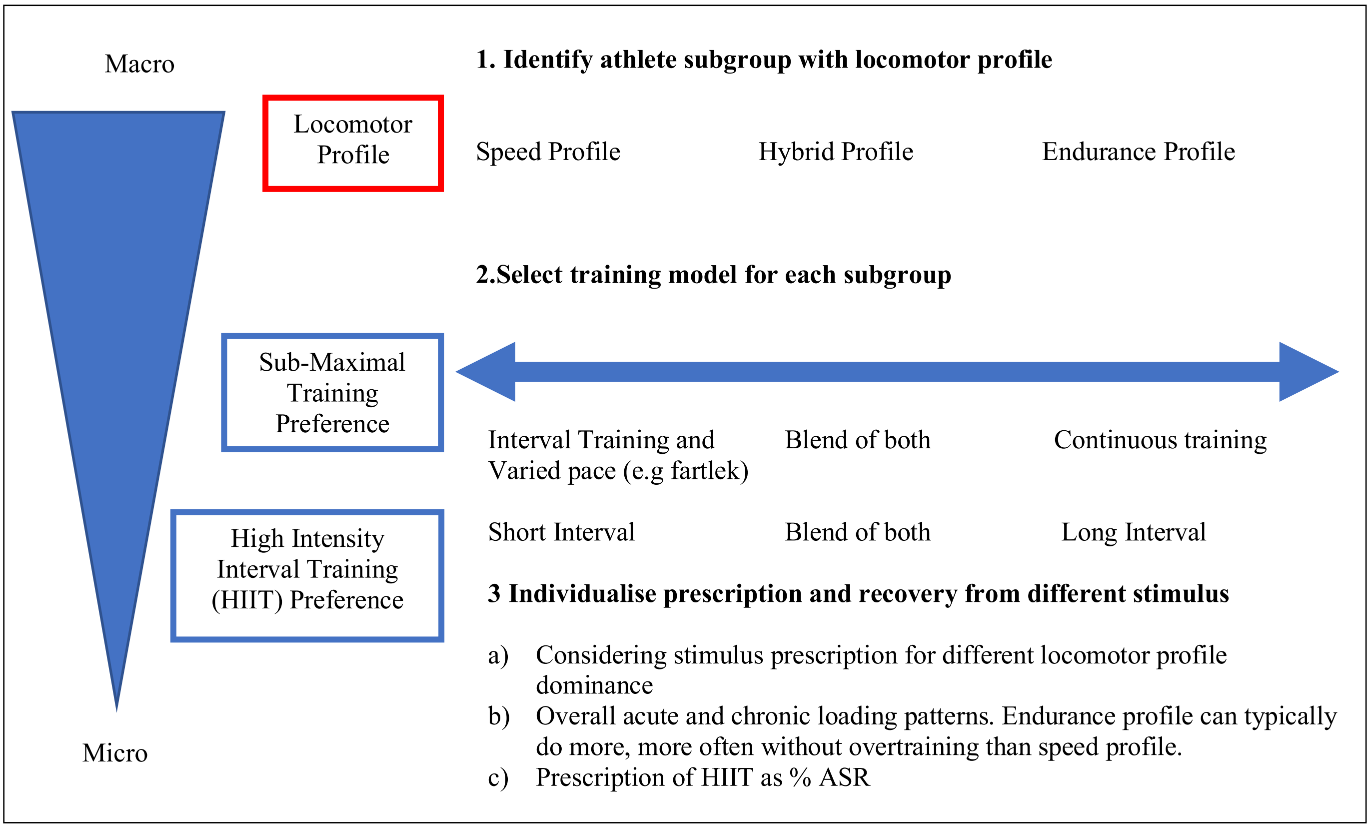


Figure 7. A practical three-step process for applying the ASR/APR construct across macro and micro training planning perspectives for a squad of diverse athlete profiles. APR anaerobic power reserve, ASR anaerobic speed reserve, HIIT high-intensity interval training. Reproduced from Sandford et al[116]

In recent years Gareth Sandford has been a proponent of the use of Anaerobic Speed Reserve[34,116–118] (ASR) to inform the training methods of endurance athletes. He has more specifically published on middle distance athletes[34]. In essence the ASR represents the difference between maximal sprinting speed and maximal aerobic speed, or vVO_2max. He recommends the profiling of athletes using these landmarks, thus allowing the rough classification of athletes as fast *vs.* endurance-based athletes along a continuum, in terms of the driver of performance. This can then guide training prescription, as it is felt that the use of ASR can allow for the consideration of other factors, such as force expression, psychological comfort/discomfort. Figure 7, reproduced below demonstrates this. The factors which limit maximal sprinting speed are not purely physiological (running technique/force expression) so it does represent a more comprehensive way reconcile physiological factors with performance factors.

Our work has focused on athletes who tend to sit more towards the endurance profile/hybrid profile of the locomotor continuum. Thus, it is felt that at the very least, the use of race pace methods to inform training at this end may be useful. Athletes who race over 5000m and above are operating below vVO_2max, and recent work[29] has suggested that successful athletes at these types of distances display very favourable fractional utilization of $\dot{V}O_{2max}$. It is not clear how ASR can allow detailed prescription for training intensities in these zones. Esfarjani and Laursen[65] demonstrated that race performance at 3000m can be improved more significantly over 10 weeks by higher intensity training, but since 3000m pace is often considered to approximate vVO_2max in runners[27,119] this is not at odds with our contention[116]

Our work has focused exclusively on endurance running, and there are some examples from other endurance sports which may offer different results/perspectives. We have argued that running is unique because generally track and road allow for consistency of terrain, and events are usually scheduled at times which facilitate consistency of climate conditions e.g. spring/autumn marathon seasons. We should, however, consider these alternatives. Ronnestad *et al*[120] showed that elite cyclists 20-minute mean power output responded better to short intervals at 94% of the maximal power output that longer intervals at 79% of max power output. The study was 3 weeks in duration, and this is a point which we will return to later, and which is acknowledged in the Filipas paper above[114]. Endurance performance, globally, is characterised by many years of training at high volume[19,121,122] so the short-term studies we see do not reflect the evolution of adaptations over the career of an endurance athlete. Filipas' paper is one of the first in runners to extend the period studied, and also to change the intensity distribution over time. Sylta[123] took a similar approach in cyclists over 12 weeks but found no difference between groups when training load was balanced across groups. The protocols were not the same, but nonetheless it is interesting to note a difference between sports

In triathlon, over the half-ironman distance[124], zone 2 training was related to better performance in recreational athletes in a study by Selles Perez *et al*. Conversely, Muñoz[125] study of 9 recreational triathletes demonstrated that the athletes, however, showed poorer outcomes when longer time was spent in training in zone 2 (measured by heart rate). Both ironman and half-ironman distances are performed mostly in zone 2[125]. In another long-distance endurance event-the Race Across America, retrospective analysis of the training of a 2nd place finisher also demonstrated that zone 2 training led to only moderate improvements in physiological variables[126].

It seems, thus, that no absolute best approach to training for performance is evident in the literature. What, then, if we focus on performance itself? This seems logical-if we know what is required for performance then the specifics of training can then be considered, whether physiologically, objectively, psychologically etc.

5.4 Endurance Performance Considerations

Since agreement has not been reached on what represents the best way to train for endurance sports it seems appropriate to start to examine endurance performance considerations, and as we are interested mostly in running performance, with a paper that studied the athletes involved in the sub 2-hour marathon performance[29]. This was a barrier considered to be theoretically possible[127] by Joyner in 2011, and as global marathon performances crept closer to it, Nike decided to make an attempt at it using some of the best athletes in the world as pacemakers. Jones *et al* presented physiological data on the athletes in question. As will be discussed in section 6.3 below fractional utilization of $\dot{V}O_2$ was the characteristic noted as most impressive among the group. The summary of factors involved in performance were eloquently described by Joyner and Coyle in a topical review piece in 2008[128]. Figure 8 summarises the determinants of performance and allows for ready visualization of how endurance performance is achieved.

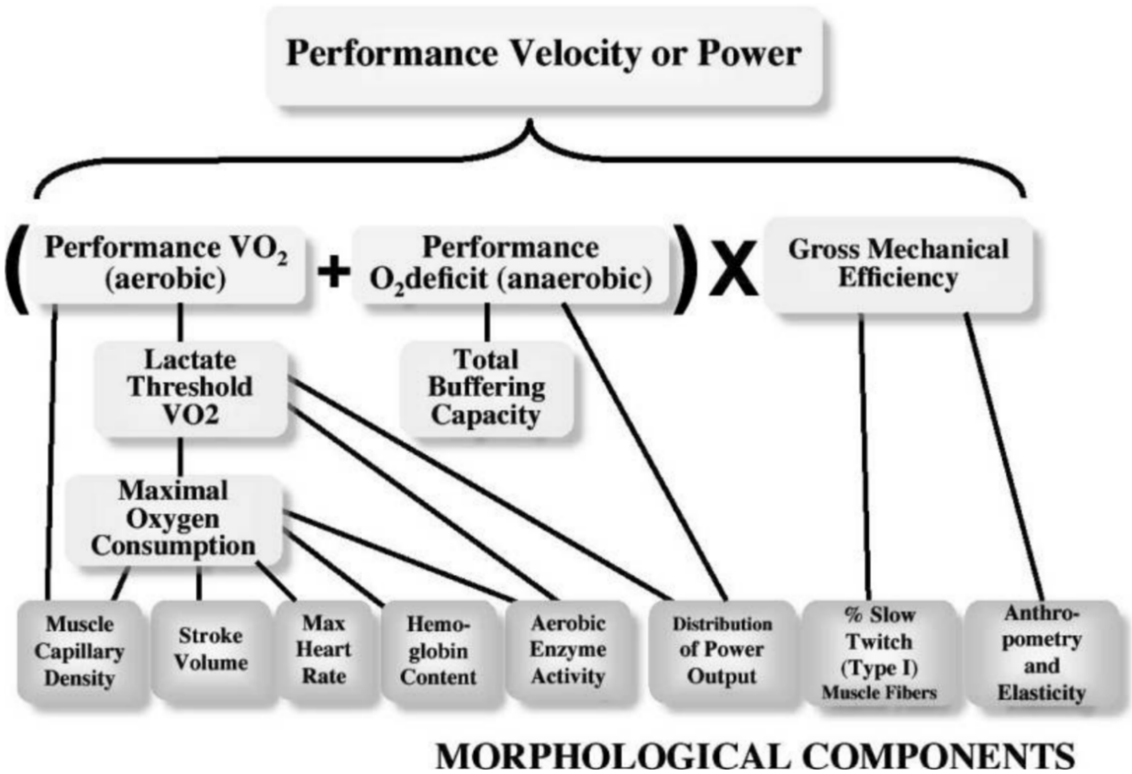


Figure 8. The physiological factors that determine performance speed according to Joyner and Coyle[24]. Overall schematic of the multiple physiological factors that interact as determinants of performance velocity or power output.

Joyner, in a classic paper from 1991[129] predicted a best theoretical time of 1:57:58 for the marathon distance, using $\dot{V}O_{2max}$, lactate threshold and running economy as inputs to his model. The values for these variables used in the paper were similar to the values reported by Jones above. So, it seems that it is reasonable to create a physiological profile in this way to model potential performance for an athlete, and that there will be bandwidths for these variables, as well as interactions between them, which will predict running performance. If it is possible to profile in this way-linking physiology to actual race performance, then training which affects any single variable with the interactions and bandwidths in mind can be guided by physiology or other means, as long as systematic monitoring is in place.

Aside from the physiological component of endurance running performance, there have been studies which have examined the pacing characteristics of world record performances[130–132]. Billat *et al*[130] examined the men's and women's marathon world records comparing them to critical speed. They found that the men's' world record was achieved at 94.7% of CS, while the women's was achieved at 96.1% of CS. The men's world record was also achieved using a negative split. Díaz *et al*[132] noted that this negative pacing approach was a more recent phenomenon when they examined the evolution of the men's marathon record over 50 years. This occurrence has led to the emergence of a new concept, which Jones notes in the paper cited above[29]: durability. This concept focusses on the ability to maintain behaviour of physiological variables over time and was discussed in a paper by Maunders, Seiler, Mildenhall, Kilding and Plews[133]. They explain that the "attributes measured during routine physiological profiling are not static, but change over time during prolonged exercise". Logic suggests that training which focusses on the improvement of physiological variables in isolation may not be capable of accounting for this phenomenon. A recent paper in cycling[134] showed that higher level riders in a grand tour could be identified by their durability, measured by ability to maintain mean power under fatigued conditions, and the pattern noted above in marathon performance suggests that athletes are performing better under fatigued conditions, because the physiological values noted by Jones do not differ significantly from those used by Joyner in his 1991 paper.

5.5 Big Data and Mathematical Modelling

Joyner's 1991 paper represented an attempt to calculate a theoretical limit to marathon performance based on what was known about the physiology of elite performers. Nowadays, there is an abundance of data collected by millions of endurance athletes daily globally, thanks to the advent of wearable technology. Heart rate, speed, power data can be easily accessed via websites such as Strava, Garmin Connect or Training Peaks. A recent trend towards simple analysis of individual datasets has been made possible, and allows for independent analysis of relevant factors to performance, without considering physiological profiling. Boullosa *et al*[135] discussed such predictions in their paper discussing factors affecting training and physical performance. They noted that use of such datasets is limited in their ability to provide training solutions because of the lack of relation to physiological parameters.

Bosquet *et al*[136] validated a simple Nomogram, first developed by Mercier[137] in the 1980s, which linked VO_{2max} to race performance. They were able to validate the nomogram for interpolated predictions, once 2 other race performances were known. Some of the authors from the 2 papers above were also involved in a paper[138] which predicted one-hour running performance from 3 shorter constant duration trials. The models could rank positions of athletes but could not accurately predict a performance. Ingham *et al*[139] used allometric modelling to try to assign weight to the determinants of performance over 800m and 1500m. They were successfully able to identify VO_{2max} and running economy as the 2 most relevant factors, and also developed an equation which allowed them to estimate the required change in a variable to improve performance.

Other attempts to use the new access to data have yielded results which more corroborate what is seen in the literature already. Zrenner[140] *et al* analysed the training of 6771 marathon finishers via an app. They identified training volume as being an identifier of better performance.

In examining this area of performance prediction, it becomes clear that divorcing physiological context from performance limits the value of the information. Alvero-Cruz *et al*[141] reviewed 58 studies which attempted to identify determinants of running performance, or predict performance. They identified 136 independent variables associated with performance in long-distance running. These variables related to derivations of the evaluation of aerobic metabolism, training load, and anthropometric characteristics. Clearly a lack of context when dealing with such a number of variables would lead to confusion.

6

LIMITATIONS & FUTURE RESEARCH

'You should never be ashamed to admit you have been wrong. It only proves you are wiser today than yesterday.'
Jonathan Swift

6 Limitations and Future Research

6.1 Limitations

Our work, and indeed the work that has followed on from it has its limitations:

- We have obviously focussed on descriptive, observational research to make a point about the direction advice on endurance sports was headed. These types of studies, however, do not provide prospective solutions, and therefore provide limited valuable new take-home advice for coaches despite what has just been described. In some ways it confirms practice.
- The results seen in our papers may not present information that many people feel they did not know already. However I believe that we have reignited this topic academically.

6.2 Future research

Future work, based on what has been presented above could focus on the following:

- Systematic profiling involving traditional physiological variables, race performance and training characteristics. This may allow for an individualised approach to preparation for performance which is feedback and feedforward driven, and can create bandwidths relating physiological profile to performance. This may include minimum individual physiological levels of endurance determinants which "allow" a specific performance, and how changes to the other determinants influence performance.

- Given that there are models now being proposed above in a number of studies[114,142,143], which suggest bases for creating a yearly training plan, based on analysis of the training of the worlds' best and integration of known physiological requirements for endurance performance, it seems contrarian to suggest a different approach. However, the collection of masses of data, both internal and external, and related to each other, on an individual basis, due to wearable technology, may offer a golden opportunity to develop really intelligent analysis for individuals to allow them to understand what works for them, and to adjust training accordingly.

- Effect of specificity of intensity on factors related to specific race performance. An example might be the effect of zone 2 training on “durability”, and subsequent marathon performance.

- Effect of specificity of intensity on psychological factors. For example, does training close to specific paces reduce the perceived effort of those paces, independent of physiological response.

- A prospective study, along the lines of design of Filipas’ paper, but over a longer period, along with regular testing and performance checkpoints seems the most logical way to shed more light.

7

CONCLUSIONS

'Let the views of others educate and inform you, but let your decisions be a product of your own conclusions'
Jim Rohn

7. Conclusions

7.1 Initial Conclusions

Even after analysing endurance running performance and training as we have above, it remains clear that nothing is clear when it comes to this topic. If we regress to a most basic level and consider the concept of performance and preparation for performance from an evolutionary perspective there is some interesting work. Boullosa *et al*[144] pose the question do Olympic athletes train as in the paleolithic era? Our ancestors from this period were resting or performing low intensity aerobic activity for long periods of time. This was then interspersed with bouts of intense physical activity; hunting and killing, followed by carrying any prize. Therefore, our evolution and adaptation to physical activity needed to reflect this. The authors note the need for specificity and individualisation, dependent on task demands but within this broad framework of a polarised approach.

Bourgois *et al*[145] further developed this concept. They noted that it was too simplistic to consider the polarised intensity of the hunter-gatherer and extrapolate to it being relevant to today. The volume of zone 2 and zone 3 equivalent intensities performed by our ancestors was much smaller than training volumes performed by elite athletes today, and energy intake and patterns are very different nowadays. They went on to consider that different TIDs may be appropriate and that there are a variety of determinants which contribute to the correct selection (Figure 9).

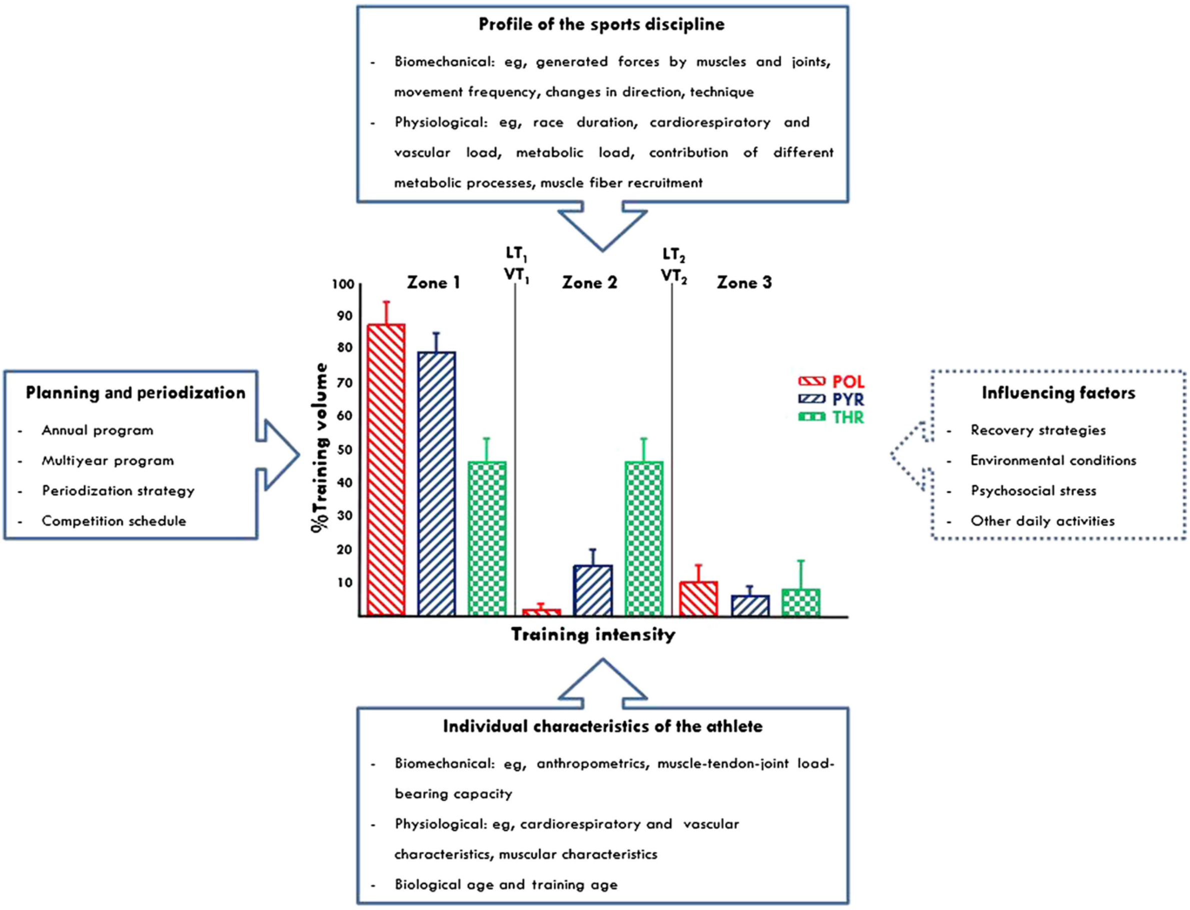


Figure 9. Models of TID and overview of the variety of evidence-based (——) and influencing (- - - -) determinants for a POL or PYR TID in elite athletes. Bourgois et al[145]

We repeatedly see that successful endurance athletes perform large volumes of training.[18,19]

We also see that the accumulation of years of training leads to better performance[121,122]. The precise detail of intensity distribution, while what is being debated, has also been shown to be variable when retrospective analysis has occurred. More recently the involvement of psychological factors has been studied increasingly. A systematic review[146] studied the effects of mental fatigue on physical performance. Increased perceived exertion was associated with decline in endurance performance, as measured by decreased time to exhaustion and self-selected power output/velocity. This was despite no effect on physiological variables associated with endurance performance or maximal performance. Duration and intensity of task were contributors to this higher perceived exertion. Delving deeper into this topic provides information from a very recent paper[147] on desire-goal motivational dynamics. Put simply, during an incremental test to exhaustion the desire to reduce effort increased, with notable shifts upwards after both lactate thresholds. So, the traditional delineators of exercise domains were also delineators of altered desire to continue to perform.

This thesis began with an underlying goal to save zone 2 or threshold training. It represents a part of many elite runners training programme, and is a personal bias, because my own performance was positively affected by using threshold training. The physiological literature had been pushing away from using zone 2, as described above. However, as has been presented it remains a part of elite and recreational endurance training. While no concrete evidence can be provided by this thesis as to its specific physiological benefit over, for example, higher intensity training, a number of reasons for its potential effects have been proposed above.

2 recent reviews have elaborated on the observations and proposals we have forwarded. Haugen *et al* very recently published a review article in Sports Medicine[142]. The paper cited the work from this thesis heavily, and described an approach to training which incorporates race-pace or external load, as "Results-Proven Practice". They review training from over 50 different athletes, available online and in books, and conclude that the volume of race-pace training increases the closer athletes get to competition, against a background of high volumes of easy running. They propose a 7-zone intensity scale for long-distance runners, which incorporates race-pace and physiological landmarks (heart rate, blood lactate etc.). They describe a seasonal pattern for both track and road distance runners, and relate physiology to race-specific considerations.

Casado *et al*[143] also reviewed this topic. They subdivided the analysis by distance-separating middle distance from long distance, and observed that in the elite athletes' training they were able to analyse from the literature it seemed that most followed a pyramidal physiological distribution for at least the early phases of seasonal training, with middle distance athletes shifting to a polarised physiological distribution closer to competition, exactly what we observed in our group above.

The authors of these articles have been able to make recommendations for endurance runners, therefore, based on the findings, contributing practically to the narrowing of the gap between science and practice. These recommendations have included running high volumes of training in zone 1, adopting a pyramidal approach to TID planning in at least the early parts of the season for all, and shifting to a polarised approach (physiologically) for middle distance athletes, while maintaining a pyramidal TID for longer distance athletes closer to competition/performance. This can also be described as becoming more task specific in later phases of training- spending more time at paces close to the target.

We would like to propose that our work in recent years has reopened discussion around this topic, and has, in part, influenced the development and creation of some of the recent studies described above.[23,61,64,114,115,135,142,148,149]

7.2 Conclusiones

Incluso después de analizar el rendimiento y el entrenamiento de la carrera de resistencia como hemos hecho anteriormente, queda claro que nada está claro en lo que respecta a este tema. Si retrocedemos al nivel más básico y consideramos el concepto de interpretación y preparación para la interpretación desde una perspectiva evolutiva, hay un trabajo interesante. Boullosa *et al*[141] plantean la pregunta ¿los atletas olímpicos entrenan como en la era paleolítica? Nuestros antepasados de esta época descansaban o realizaban actividad aeróbica de baja intensidad durante largos períodos de tiempo. Esto luego se intercalaba con episodios de intensa actividad física; cazar y matar, seguido de llevar cualquier premio. Por lo tanto, nuestra evolución y adaptación a la actividad física necesitaba reflejar esto. Los autores señalan la necesidad de especificidad e individualización, dependiendo de las demandas de la tarea, pero dentro de este amplio marco de un enfoque polarizado.

Bourgois *et al*[142] desarrollaron aún más este concepto. Señalaron que era demasiado simplista considerar la intensidad polarizada del cazador-recolector y extrapolarlo a su relevancia actual. El volumen de las intensidades equivalentes de la Zona 2 y la Zona 3 realizadas por nuestros antepasados era mucho menor que los volúmenes de entrenamiento realizados por los atletas de élite en la actualidad, y la ingesta de energía y los patrones son muy diferentes hoy en día. Continuaron considerando que diferentes TID pueden ser apropiados y que hay una variedad de determinantes que contribuyen a la selección correcta (Figura 9).

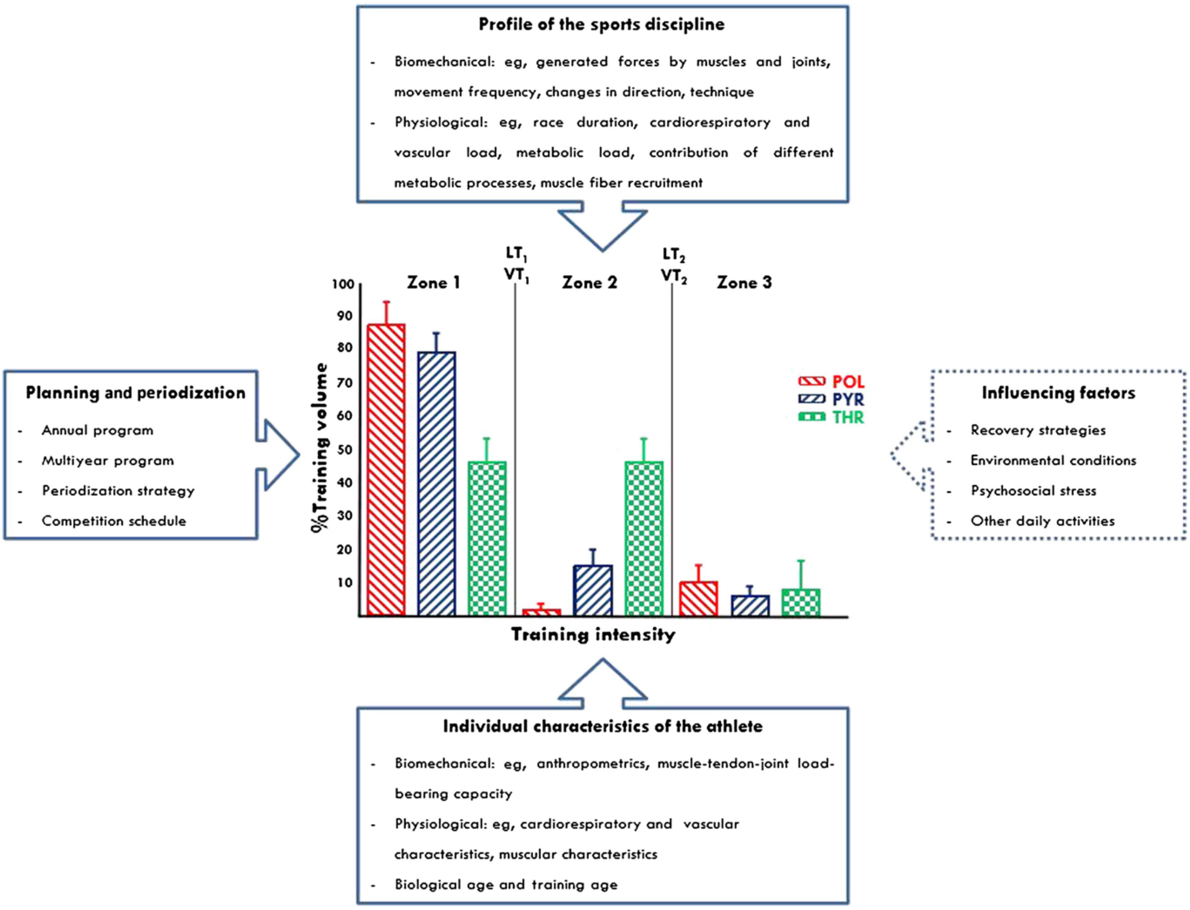


Figura 9. Modelos de TID y descripción general de la variedad de determinantes basados en evidencia (–––) e influyentes (- - - -) para un POL o PYR TID en atletas de élite. Bourgois et al[145]

Vemos repetidamente que los atletas de resistencia exitosos realizan grandes volúmenes de entrenamiento.[18,19]

Vemos también que la acumulación de años de formación conduce a un mejor rendimiento[118,119]. El detalle preciso de la distribución de la intensidad, si bien es lo que se debate, también se ha demostrado que es variable cuando se ha producido un análisis retrospectivo. Más recientemente, la participación de factores psicológicos se ha estudiado cada vez más. Una revisión sistemática[143] estudió los efectos de la fatiga mental en el rendimiento físico. El aumento del esfuerzo percibido se asoció con la disminución del rendimiento de resistencia, medido por la disminución del tiempo hasta el agotamiento y la producción de potencia/velocidad autoseleccionadas. Esto fue a pesar de que no hubo efecto sobre las variables fisiológicas asociadas con el rendimiento de resistencia o el rendimiento máximo. La duración y la intensidad de la tarea contribuyeron a este mayor esfuerzo percibido. Profundizar en este tema proporciona información de un artículo muy reciente[144] sobre la dinámica motivacional deseo-meta. En pocas palabras, durante una prueba incremental hasta el agotamiento aumentó el deseo de reducir el esfuerzo, con cambios notables hacia arriba después de ambos umbrales de lactato. Entonces, los delineadores tradicionales de los dominios de ejercicio también fueron delineadores del deseo alterado de continuar realizando.

Esta tesis comenzó con el objetivo subyacente de salvar la Zona 2 o el entrenamiento de umbral. Representa una parte del programa de entrenamiento de muchos corredores de élite y es un sesgo personal, porque mi propio rendimiento se vio afectado positivamente al usar el entrenamiento de umbral. La literatura fisiológica se había alejado del uso de la Zona 2, como se describe anteriormente. Sin embargo, como se ha presentado, sigue siendo parte del entrenamiento de resistencia recreativo y de élite. Si bien esta tesis no puede proporcionar evidencia concreta en cuanto a su beneficio fisiológico específico sobre, por ejemplo, el entrenamiento de mayor intensidad, anteriormente se han propuesto varias razones para sus efectos potenciales.

2 revisiones recientes han desarrollado las observaciones y propuestas que hemos sugerido. Haugen *et al* publicaron muy recientemente un artículo de revisión en *Sports Medicine*[139]. El documento citó en gran medida el trabajo de esta tesis y describió un enfoque de entrenamiento que incorpora el ritmo de carrera o la carga externa, como "*Práctica comprobada por resultados*". Revisan el entrenamiento de más de 50 atletas diferentes, disponibles en línea y en libros, y concluyen que el volumen de entrenamiento a ritmo de carrera aumenta a medida que los atletas se acercan a la competencia, en un contexto de grandes volúmenes de carrera fácil. Proponen una escala de intensidad de 7 zonas para corredores de larga distancia, que incorpora puntos de referencia fisiológicos y de ritmo de carrera (frecuencia cardíaca, lactato en sangre, etc.). Describen un patrón estacional para los corredores de larga distancia tanto en pista como en carretera, y relacionan la fisiología con consideraciones específicas de la carrera.

Casado *et al*[140] también revisaron este tema. Subdividieron el análisis por distancia, separando la distancia media de la distancia larga, y observaron que en el entrenamiento de los atletas de élite que pudieron analizar de la literatura parecía que la mayoría seguía una distribución fisiológica piramidal durante al menos las primeras fases del entrenamiento estacional. con atletas de media distancia cambiando a una distribución fisiológica polarizada más cercana a la competencia, exactamente lo que observamos en nuestro grupo anterior.

Los autores de estos artículos han podido hacer recomendaciones para los corredores de resistencia, por lo tanto, en base a los hallazgos, han contribuido prácticamente a reducir la brecha entre la ciencia y la práctica. Estas recomendaciones han incluido realizar grandes volúmenes de entrenamiento en la Zona 1, adoptar un enfoque piramidal para la planificación de TID en al menos las primeras partes de la temporada para todos, y cambiar a un enfoque polarizado (fisiológicamente) para atletas de media distancia, manteniendo un enfoque piramidal. TID para atletas de larga distancia más cerca de la competencia/rendimiento. Esto también se puede describir como una tarea más específica en las fases posteriores del entrenamiento, pasando más tiempo a ritmos cercanos al objetivo.

Nos gustaría proponer que nuestro trabajo en los últimos años ha reabierto la discusión en torno a este tema y, en parte, ha influido en el desarrollo y la creación de algunos de los estudios recientes descritos anteriormente.[23,61,64,111,112,132,139,145,146]

7.3 Final Conclusions

In commencing this thesis I aimed to try to better understand my perception of a gap between advice from sports scientists regarding training prescription, and the reality of what was going on at the elite level of endurance running. I entered into the research with my eyes wide open to my own biases. I favoured the use of threshold and race-pace sessions and noted that many of the worlds' best coaches used race paces as a reference for training sessions. But a building body of evidence suggested that polarised type training was best for endurance sport. So how could this circle be squared logically.

The notion of using race-pace as a reference point seemed a starting point as this is what my bias was based on, and making an assumption that the training of elite athletes was somewhat optimised through years of trial and error, the research plan was built. With the intention of suggesting that perhaps this training wasn't optimised And what can we conclude from the work we did?

Conclusion 1: Elite runners run a lot, and 80-90% of their training is zone 1 (physiologically or race-pace). This is not new.

Conclusion 2: There is conflicting evidence on the optimal TID based on physiological parameters, but both polarised and pyramidal types are employed. Most interventional studies are based on relatively short periods of time, and endurance performance is built over much longer periods. More recently the use of a pyramidal distribution, followed by polarised closer to target performance was tested interventionally and was successful.

Conclusion 3: When using race-pace as a reference point it becomes clear that training prescription, in some way, takes this into account. There is a consistent organisation of training in the group we studied whereby regardless of race distance, volumes of training at paces relative to race pace are pretty consistent.

Of course there are limitations to this approach. It is clear that the zone creation for race-pace based analysis was arbitrary and imperfect, and the historical physiological determinants of endurance capacity are well established and are also very consistent, but nonetheless it is proposed that a strong case for the use of "results-driven" training prescription exists.

Conclusion 4: There are likely base levels for the physiological determinants which "allow" particular bandwidths of performance. How well an athlete then performs within the bandwidth then likely depends on the interaction between determinants, and how much an athlete depends on a particular characteristic to support their performance.

Conclusion 5: The emergence of the concept of durability is something which may help to further elucidate important individual performance determinants. Submaximal tests which look at physiological responses to fixed workloads may be more palatable to many coaches than regular tests beyond vLT2 and stability/instability of certain characteristic strengths and weaknesses may help link physiology to performance.

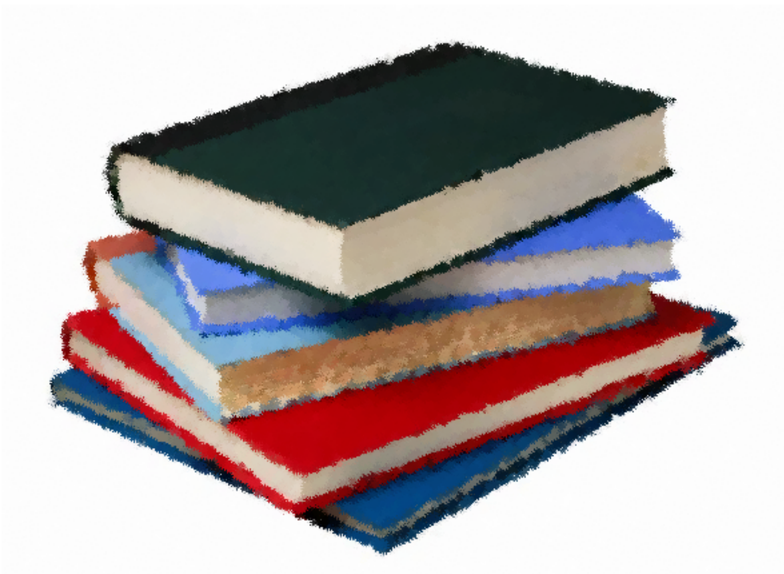
Conclusion 6: Currently physiological testing seems to be utilised infrequently amongst many elite runners, and it is suggested that this is because systematic links are not being made between training-induced physiological changes and performance changes.

Conclusion 7: The use of data from training apps such as Strava may become useful in further developing this area of research as timestamped performance and physiological data may co-exist on the same platform in high volume

8

REFERENCES

'If a man brings references, it proves nothing; but if he can't, it proves a great deal'
Joseph Pulitzer



8. References

1. Kenneally M, Casado A, Gomez-Ezeiza J, Santos-Concejero J. Training intensity distribution analysis by race pace vs. physiological approach in world-class middle- and long-distance runners. *European Journal of Sport Science*. 2021;21(6). doi:10.1080/17461391.2020.1773934
2. Kenneally M, Casado A, Gomez-Ezeiza J, Santos-Concejero J. Training Characteristics of a World Championship 5000-m Finalist and Multiple Continental Record Holder Over the Year Leading to a World Championship Final. *International Journal of Sports Physiology and Performance*. Published online 2021:1-5. doi:10.1123/ijspp.2021-0114
3. Kenneally M, Casado A, Santos-Concejero J. The effect of periodization and training intensity distribution on middle-and long-distance running performance: A systematic review. *International Journal of Sports Physiology and Performance*. 2018;13(9). doi:10.1123/ijspp.2017-0327
4. Bellinger P, Arnold B, Minahan C. Quantifying the training-intensity distribution in middle-distance runners: The influence of different methods of training-intensity quantification. *International Journal of Sports Physiology and Performance*. 2020;15(3):319-323. doi:10.1123/ijspp.2019-0298
5. Coyle EF. Integration of the physiological factors determining endurance performance ability. *Exercise and Sport Sciences Reviews*. 1995;23(1):25-63. doi:10.1249/00003677-199500230-00004
6. Allen WK, Seals DR, Hurley BF, Ehsani AA, Hagberg JM. Lactate threshold and distance-running performance in young and older endurance athletes. *Journal of Applied Physiology*. 1985;58(4):1281-1284. doi:10.1152/jappl.1985.58.4.1281
7. Conley DL, Krahenbuhl GS. Running economy and distance running performance of highly trained athletes. *Medicine and Science in Sports and Exercise*. 1980;12(5):357-360. doi:10.1249/00005768-198025000-00010
8. McLaughlin JE, Howley ET, Bassett DR, Thompson DL, Fitzhugh EC. Test of the classic model for predicting endurance running performance. *Medicine and Science in Sports and Exercise*. 2010;42(5):991-997. doi:10.1249/MSS.0b013e3181c0669d
9. Tim Noakes. *Lore of Running*. 4th ed. Human Kinetics; 2005.
10. Renfree A. andrewrenfree.wordpress.com.
11. Kilic K, Ince ML. Use of Sports Science Knowledge by Turkish Coaches. *Int J Exerc Sci*. 8(1):21-37.
12. Kubayi A, Coopoo Y, Toriola A. Analysis of sport science perceptions and research needs among South African coaches. *South African Journal of Sports Medicine*. 2018;30(1):1-4. doi:10.17159/2078-516X/2018/v30i1a4240
13. Reade I, Rodgers W, Hall N. Knowledge Transfer: How do High Performance Coaches Access the Knowledge of Sport Scientists? *International Journal of Sports Science & Coaching*. 2008;3(3):319-334. doi:10.1260/174795408786238470
14. Williams SJ, Kendall L. Perceptions of elite coaches and sports scientists of the research needs for elite coaching practice. *Journal of Sports Sciences*. 2007;25(14):1577-1586. doi:10.1080/02640410701245550
15. Takashima W, Ishii K, Takizawa K, Yamaguchi T, Nosaka K. Muscle damage and soreness following a 50-km cross-country ski race. *European Journal of Sport Science*. 2007;7(1):27-33. doi:10.1080/17461390701197833

16. Seiler KS, Kjerland GØ. Quantifying training intensity distribution in elite endurance athletes: Is there evidence for an "optimal" distribution? *Scandinavian Journal of Medicine and Science in Sports*. 2006;16(1):49-56. doi:10.1111/j.1600-0838.2004.00418.x
17. Seiler S. What is best practice for training intensity and duration distribution in endurance athletes? *International Journal of Sports Physiology and Performance*. 2010;5(3):276-291. doi:10.1123/ijspp.5.3.276
18. Enoksen E, Tjelta AR, Tjelta LI. Distribution of training volume and intensity of elite male and female track and marathon runners. *International Journal of Sports Science and Coaching*. 2011;6(2):273-293. doi:10.1260/1747-9541.6.2.273
19. Tjelta LI. The training of international level distance runners. *International Journal of Sports Science and Coaching*. 2016;11(1):122-134. doi:10.1177/1747954115624813
20. Tjelta LI. Three Norwegian brothers all European 1500 m champions: What is the secret? *International Journal of Sports Science and Coaching*. 2019;14(5):694-700. doi:10.1177/1747954119872321
21. Tjelta LI, Enoksen E. Training characteristics of male junior cross country and track runners on European top level. *International Journal of Sports Science and Coaching*. 2010;5(2):193-203. doi:10.1260/1747-9541.5.2.193
22. Tjelta L, Tønnessen E, Enoksen E. A case study of the training of nine times New York Marathon winner Grete Waitz. *International Journal of Sports Science and Coaching*. 2014;9(1):139-157. doi:10.1260/1747-9541.9.1.139
23. Casado A, Hanley B, Santos-Concejero J, Ruiz-Pérez LM. World-class long-distance running performances are best predicted by volume of easy runs and deliberate practice of short-interval and tempo runs. *Journal of Strength and Conditioning Research*. 2021;35(9):2525-2531. doi:10.1519/JSC.0000000000003176
24. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *The Journal of Physiology*. 2008;586(1):35-44. doi:10.1113/jphysiol.2007.143834
25. Billat LV. Use of Blood Lactate Measurements for Prediction of Exercise Performance and for Control of Training. *Sports Medicine*. 1996;22(3):157-175. doi:10.2165/00007256-199622030-00003
26. Billat V, Bernard O, Pinoteau J, Petit B, Koralsztein JP. Time to exhaustion at VO2 max and lactate steady state velocity in sub elite long-distance runners. *Archives Internationales de Physiologie, de Biochimie et de Biophysique*. 1994;102(3):215-219. doi:10.3109/13813459409007541
27. Billat LV, Koralzstein JP. Significance of the Velocity at VO2max and Time to Exhaustion at this Velocity. *Sports Medicine*. 1996;22(Aug):90-108.
28. Esteve-Lanao J, Foster C, Seiler S, Lucia A. Impact of Training Intensity Distribution on Performance in Endurance Athletes. *The Journal of Strength and Conditioning Research*. 2007;21(3):943. doi:10.1519/R-19725.1
29. Jones AM, Kirby BS, Clark IE, et al. Physiological demands of running at 2-hour marathon race pace. *Journal of Applied Physiology*. 2021;130(2):369-379. doi:10.1152/japplphysiol.00647.2020
30. Emig T, Peltonen J. Human running performance from real-world big data. *Nature Communications*. 2020;11(1):4936. doi:10.1038/s41467-020-18737-6
31. Ingham SA, Whyte GP, Pedlar C, Bailey DM, Dunman N, Nevill AM. Determinants of 800-m and 1500-m Running Performance Using Allometric

Models. *Medicine & Science in Sports & Exercise*. 2008;40(2):345-350. doi:10.1249/mss.0b013e31815a83dc
32. Seiler S, Tonnessen E. Intervals, threshold and long slow distance: the role of intensity and duration in endurance training. *Sports Science*. 2009;13:32-53.
33. Cerezuela-Espejo V, Courel-Ibáñez J, Morán-Navarro R, Martínez-Cava A, Pallarés JG. The Relationship Between Lactate and Ventilatory Thresholds in Runners: Validity and Reliability of Exercise Test Performance Parameters. *Frontiers in Physiology*. 2018;9. doi:10.3389/fphys.2018.01320
34. Sandford GN, Allen SV, Kilding AE, Ross A, Laursen PB. Anaerobic speed reserve: A key component of elite Male 800-m running. *International Journal of Sports Physiology and Performance*. 2019;14(4):501-508. doi:10.1123/ijspp.2018-0163
35. Foster C, Florhaug JA, Franklin J, et al. A New Approach to Monitoring Exercise Training. *Journal of Strength and Conditioning Research*. 2001;15(1):109-115. doi:10.1519/00124278-200102000-00019
36. Munoz I, Seiler S, Alcocer A, Carr N, Esteve-Lanao J. Specific Intensity for Peaking: Is Race Pace the Best Option? *Asian Journal of Sports Medicine*. 2015;6(3). doi:10.5812/asjsm.24900
37. Arcelli E, Canova R. *Scientific Training for the Marathon*.; 1999.
38. Burnley M, Jones AM. Power–duration relationship: Physiology, fatigue, and the limits of human performance. *European Journal of Sport Science*. 2018;18(1):1-12. doi:10.1080/17461391.2016.1249524
39. Casado A, Hanley B, Ruiz-Pérez LM. Deliberate practice in training differentiates the best Kenyan and Spanish long-distance runners. *European Journal of Sport Science*. 2020;20(7):887-895. doi:10.1080/17461391.2019.1694077
40. Issurin VB. New Horizons for the Methodology and Physiology of Training Periodization. *Sports Medicine*. 2010;40(3):189-206. doi:10.2165/11319770-000000000-00000
41. Selye H. Stress and the General Adaptation Syndrome. *BMJ*. 1950;1(4667):1383-1392. doi:10.1136/bmj.1.4667.1383
42. Kiely J. Periodization Theory: Confronting an Inconvenient Truth. *Sports Medicine*. 2018;48(4):753-764. doi:10.1007/s40279-017-0823-y
43. Mølmen KS, Øfsteng SJ, Rønnestad BR. <p>Block periodization of endurance training – a systematic review and meta-analysis</p>. *Open Access Journal of Sports Medicine*. 2019;Volume 10:145-160. doi:10.2147/OAJSM.S180408
44. Issurin VB. Benefits and Limitations of Block Periodized Training Approaches to Athletes' Preparation: A Review. *Sports Medicine*. 2016;46(3):329-338. doi:10.1007/s40279-015-0425-5
45. Bondarchuk A. *Transfer of Training in Sports*.
46. Seiler S, Kjerland G. Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? *Scandinavian Journal of Medicine and Science in Sports*. 2006;16:49-56.
47. Esteve-Lanao J, Foster C, Seiler S, Lucia A. Impact of training intensity distribution on performance in endurance athletes. *Journal of Strength and Conditioning Research*. 2007;21(3):943-949. doi:10.1519/R-19725.1
48. Muñoz I, Seiler S, Bautista J, España J, Larumbe E, Esteve-Lanao J. Does polarized training improve performance in recreational runners? *International Journal of Sports Physiology and Performance*. 2014;9(2):265-272. doi:10.1123/IJSPP.2012-0350
49. Magness S. scienceofrunning.com.

50. Leinonen M. *Back to the Top: Perspectives and Snapshots of Finnish Enurance Running Coaching in the 1970s*. 2005.
51. Horwill F. Frank Horwill Training Philosophy. 2012.
52. Seiler S. A Brief History of Endurance Testing in Athletes. *Sportscience*. Published online 2011.
53. Hill A v., Lupton H. Muscular Exercise, Lactic Acid, and the Supply and Utilization of Oxygen. *QJM*. 1923;os-16(62):135-171. doi:10.1093/qjmed/os-16.62.135
54. Costill D, Thomason H, Roberts E. Fractional utilization of the aerobic capacity during distance running. *Medicine and Science in Sports*. 1973;5(4):248-252.
55. Lydiard A, Gilmour G. *Running with Lydiard*.; 1978.
56. Stöggl T, Sperlich B. Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. *Frontiers in Physiology*. 2014;5 FEB. doi:10.3389/fphys.2014.00033
57. Stöggl TL, Sperlich B. The training intensity distribution among well-trained and elite endurance athletes. *Frontiers in Physiology*. 2015;6(OCT):295. doi:10.3389/fphys.2015.00295
58. Billat VL, Demarle A, Slawinski J, Paiva M, Koralsztein JP. Physical and training characteristics of top-class marathon runners. *Medicine and Science in Sports and Exercise*. 2001;33(12):2089-2097. doi:10.1097/00005768-200112000-00018
59. Billat V, Lepretre PM, Heugas AM, Laurence MH, Salim D, Koralsztein JP. Training and bioenergetic characteristics in elite male and female Kenyan runners. *Medicine and Science in Sports and Exercise*. 2003;35(2):297-304. doi:10.1249/01.MSS.0000053556.59992.A9
60. Stellingwerff T. Training of Eliud Kipchoge leading into the Berlin Marathon 2017. Twitter .@TStellingwerff.
61. Haugen T, Sandbakk Ø, Enoksen E, Seiler S, Tønnessen E. Crossing the Golden Training Divide: The Science and Practice of Training World-Class 800- and 1500-m Runners. *Sports Medicine*. 2021;51(9):1835-1854. doi:10.1007/s40279-021-01481-2
62. Parmar A, Jones T, Hayes P. The use of interval-training methods by coaches of well-trained middle- to long-distance runners. *International Journal of Strength and Conditioning*. 2021;1(1). doi:10.47206/ijsc.v1i1.54
63. Burnley M, Bearden SE, Jones AM. Polarized Training is Not Optimal for Endurance Athletes. *Medicine & Science in Sports & Exercise*. Published online February 9, 2022. doi:10.1249/MSS.0000000000002869
64. Foster C, Casado A, Esteve-Lanao J, Haugen T, Seiler S. Polarized Training is Optimal for Endurance Athletes. *Medicine and Science in Sports and Exercise*. Published online February 2022.
65. Esfarjani F, Laursen PB. Manipulating high-intensity interval training: Effects on , the lactate threshold and 3000m running performance in moderately trained males. *Journal of Science and Medicine in Sport*. 2007;10(1):27-35. doi:10.1016/j.jsams.2006.05.014
66. Yoshida T, Suda Y, Takeuchi N. Endurance training regimen based upon arterial blood lactate: Effects on anaerobic threshold. *European Journal of Applied Physiology and Occupational Physiology*. 1982;49(2):223-230. doi:10.1007/BF02334071
67. Enoksen E, Shalfawi SAI, Tønnessen E. The Effect of High- vs. Low-Intensity Training on Aerobic Capacity in Well-Trained Male Middle-Distance Runners.

Journal of Strength and Conditioning Research. 2011;25(3):812-818. doi:10.1519/JSC.0b013e3181cc2291

68. Bideau N. Personal Conversations and emails.
69. Oxford Centre for Evidence-based Medicine. Levels of Evidence. *University of Oxford*. Published online 2009.
70. de Morton NA. The PEDro scale is a valid measure of the methodological quality of clinical trials: a demographic study. *Australian Journal of Physiotherapy*. 2009;55(2):129-133. doi:10.1016/S0004-9514(09)70043-1
71. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Laurence Erlbaum Associates; 1988.
72. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*. 2009;41(1):3-12. doi:10.1249/MSS.0b013e31818cb278
73. Bourdon PC. Blood Lactate Thresholds: Concepts and Applications. In: Tanner RK, Gore CJ, eds. *Physiological Tests for Elite Athletes*. Human Kinetics; 2013.
74. Haugen T. Best-Practice Coaches: An Untapped Resource in Sport-Science Research. *International Journal of Sports Physiology and Performance*. 2021;16(9):1215-1216. doi:10.1123/ijspp.2021-0277
75. Faulkner JA. New Perspectives in Training for Maximum Performance. *JAMA: The Journal of the American Medical Association*. 1968;205(11):741-746. doi:10.1001/jama.1968.03140370043009
76. Stoggl T, Sperlich B. Polarised training has greater impact on key endurance variables than threshold, high intensity, or high volume training. *Frontiers in Physiology*. 2014;5(33).
77. Rosenblat MA, Perrotta AS, Vicenzino B. Polarized vs. Threshold Training Intensity Distribution on Endurance Sport Performance: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. *J Strength Cond Res*. 2019;33(12):3491-3500. doi:10.1519/JSC.0000000000002618
78. Clemente-Suarez VJ, Dalamitros AA, Nikolaidis PT. The effect of a short-term training period on physiological parameters and running performance: Intensity distribution versus constant-intensity exercise. *Journal of Sports Medicine and Physical Fitness*. 2018;58(1-2):1-7. doi:10.23736/S0022-4707.16.06756-6
79. Clemente Suárez VJ, González-Ravé JM. Four weeks of training with different aerobic workload distributions - Effect on aerobic performance. *European Journal of Sport Science*. 2014;14(SUPPL.1). doi:10.1080/17461391.2011.635708
80. Manzi V, Bovenzi A, Castagna C, Salimei PS, Volterrani M, Iellamo F. Training-load distribution in endurance runners: Objective versus subjective assessment. *International Journal of Sports Physiology and Performance*. 2015;10(8):1023-1028. doi:10.1123/ijspp.2014-0557
81. Robinson DM, Robinson SM, Hume PA, Hopkins WG. Training intensity of elite male distance runners. *Medicine and Science in Sports and Exercise*. 1991;23(9):1078-1082. doi:10.1249/00005768-199109000-00013
82. Esteve-Lanao J, San Juan AF, Earnest CP, Foster C, Lucia A. How do endurance runners actually train? Relationship with competition performance. *Medicine and Science in Sports and Exercise*. 2005;37(3):496-504. doi:10.1249/01.MSS.0000155393.78744.86
83. Leif Inge Tjelta. A Longitudinal Case Study of the Training of the 2012 European 1500m Track Champion. *IJASS(International Journal of Applied Sports Sciences)*. 2013;25(1):11-18. doi:10.24985/ijass.2013.25.1.11

84. Stoggl T, Sperlich B. The training intensity distribution among well-trained and elite endurance athletes. *Frontiers in Physiology*. 2015;6(295).
85. Stellingwerff T. Case study: Nutrition and training periodization in three elite marathon runners. *International Journal of Sport Nutrition and Exercise Metabolism*. 2012;22(5):392-400. doi:10.1123/ijsnem.22.5.392
86. Ingham SA, Fudge BW, Pringle JS. Training distribution, physiological profile, and performance for a male international 1500-m runner. *International Journal of Sports Physiology and Performance*. 2012;7(2):193-195. doi:10.1123/ijspp.7.2.193
87. Mujika I. Quantification of training and competition loads in endurance sports: Methods and applications. *International Journal of Sports Physiology and Performance*. 2017;12:9-17. doi:10.1123/ijspp.2016-0403
88. Weyand P, Curcton K, Conley D, Sloniger M. Percentage Anaerobic Energy utilized during Track Running Events. *Medicine & Science in Sports & Exercise*. 1993;25(Supplement):S105. doi:10.1249/00005768-199305001-00588
89. Fiskerstrand Å, Seiler KS. Training and performance characteristics among Norwegian International Rowers 1970-2001. *Scandinavian Journal of Medicine and Science in Sports*. 2004;14(5):303-310. doi:10.1111/j.1600-0838.2003.00370.x
90. Foster C, Rodriguez-Marroyo JA, de Koning JJ. Monitoring training loads: The past, the present, and the future. *International Journal of Sports Physiology and Performance*. 2017;12:2-8. doi:10.1123/IJSPP.2016-0388
91. Festa L, Tarperi C, Skroce K, la Torre A, Schena F. Effects of Different Training Intensity Distribution in Recreational Runners. *Frontiers in Sports and Active Living*. 2020;1. doi:10.3389/fspor.2019.00070
92. Tønnessen E, Sylta Ø, Haugen TA, Hem E, Svendsen IS, Seiler S. The Road to Gold: Training and Peaking Characteristics in the Year Prior to a Gold Medal Endurance Performance. *PLoS ONE*. 2014;9(7):e101796. doi:10.1371/journal.pone.0101796
93. Jack Daniels. *Daniels' Running Formula* . 2nd ed.; 2005.
94. Poole DC, Rossiter HB, Brooks GA, Gladden LB. The anaerobic threshold: 50+ years of controversy. *The Journal of Physiology*. 2021;599(3):737-767. doi:10.1113/JP279963
95. Jamnick NA, Pettitt RW, Granata C, Pyne DB, Bishop DJ. An Examination and Critique of Current Methods to Determine Exercise Intensity. *Sports Medicine*. 2020;50(10):1729-1756. doi:10.1007/s40279-020-01322-8
96. Monod H, Scherrer J. The Work Capacity of a Synergic Muscular Group. *Ergonomics*. 1965;8(3):329-338. doi:10.1080/00140136508930810
97. Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC. Critical Power: Implications for Determination of V˙O2max and Exercise Tolerance. *Medicine & Science in Sports & Exercise*. 2010;42(10):1876-1890. doi:10.1249/MSS.0b013e3181d9cf7f
98. Burnley M, Jones AM. Power–duration relationship: Physiology, fatigue, and the limits of human performance. *European Journal of Sport Science*. 2018;18(1):1-12. doi:10.1080/17461391.2016.1249524
99. Jones AM, Vanhatalo A. The 'Critical Power' Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. *Sports Medicine*. 2017;47(S1):65-78. doi:10.1007/s40279-017-0688-0

100. Vanhatalo A, Jones AM, Burnley M. Application of Critical Power in Sport. *International Journal of Sports Physiology and Performance*. 2011;6(1):128-136. doi:10.1123/ijspp.6.1.128
101. Poole DC, Burnley M, Vanhatalo A, Rossiter HB, Jones AM. Critical Power. *Medicine & Science in Sports & Exercise*. 2016;48(11):2320-2334. doi:10.1249/MSS.0000000000000939
102. Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC. Critical Power: Implications for Determination of V˙O2max and Exercise Tolerance. *Medicine & Science in Sports & Exercise*. 2010;42(10):1876-1890. doi:10.1249/MSS.0b013e3181d9cf7f
103. Jones AM, Burnley M, Black MI, Poole DC, Vanhatalo A. The maximal metabolic steady state: redefining the 'gold standard.' *Physiological Reports*. 2019;7(10):e14098. doi:10.14814/phy2.14098
104. Poole DC, Jones AM. Oxygen Uptake Kinetics. In: *Comprehensive Physiology*. Wiley; 2012:933-996. doi:10.1002/cphy.c100072
105. Dekerle J, Nesi X, Carter H. The distance – time relationship over a century of running Olympic performances: A limit on the critical speed concept. *Journal of Sports Sciences*. 2006;24(11):1213-1221. doi:10.1080/02640410500497642
106. Vandewalle H, Vautier JF, Kachouri M, Lechevalier JM, Monod H. Work-exhaustion time relationships and the critical power concept. A critical review. *J Sports Med Phys Fitness*. 1997;37(2):89-102.
107. Bosquet L, Duchene A, Lecot F, Dupont G, Leger L. V max estimate from three-parameter critical velocity models: validity and impact on 800 m running performance prediction. *European Journal of Applied Physiology*. 2006;97(1):34-42. doi:10.1007/s00421-006-0143-7
108. Patoz A, Pedrani N, Spicher R, Berchtold A, Borrani F, Malatesta D. Effect of Mathematical Modeling and Fitting Procedures on the Assessment of Critical Speed and Its Relationship With Aerobic Fitness Parameters. *Frontiers in Physiology*. 2021;12. doi:10.3389/fphys.2021.613066
109. Iannetta D, Ingram CP, Keir DA, Murias JM. Methodological Reconciliation of CP and MLSS and Their Agreement with the Maximal Metabolic Steady State. *Medicine & Science in Sports & Exercise*. 2021;Ahead of Print.
110. Kirby BS, Winn BJ, Wilkins BW, Jones AM. Interaction of exercise bioenergetics with pacing behavior predicts track distance running performance. *Journal of Applied Physiology*. 2021;131(5):1532-1542. doi:10.1152/japplphysiol.00223.2021
111. Pettitt RW. Applying the Critical Speed Concept to Racing Strategy and Interval Training Prescription. *International Journal of Sports Physiology and Performance*. 2016;11(7):842-847. doi:10.1123/ijspp.2016-0001
112. Black MI, Simpson LP, Goulding RP, Spragg J. A critique of "A critical review of critical power." *European Journal of Applied Physiology*. 2022;122(7):1745-1746. doi:10.1007/s00421-022-04959-7
113. Dotan R. A critical review of critical power. *European Journal of Applied Physiology*. 2022;122(7):1559-1588. doi:10.1007/s00421-022-04922-6
114. Filipas L, Bonato M, Gallo G, Codella R. Effects of 16 weeks of pyramidal and polarized training intensity distributions in well-trained endurance runners. *Scandinavian Journal of Medicine & Science in Sports*. Published online November 25, 2021. doi:10.1111/sms.14101
115. Matzka M, Leppich R, Sperlich B, Zinner C. Retrospective Analysis of Training Intensity Distribution Based on Race Pace Versus Physiological Benchmarks in

Highly Trained Sprint Kayakers. *Sports Medicine - Open*. 2022;8(1):1. doi:10.1186/s40798-021-00382-y

116. Sandford GN, Laursen PB, Buchheit M. Anaerobic Speed/Power Reserve and Sport Performance: Scientific Basis, Current Applications and Future Directions. *Sports Medicine*. 2021;51(10):2017-2028. doi:10.1007/s40279-021-01523-9
117. Sandford GN, Kilding AE, Ross A, Laursen PB. Maximal Sprint Speed and the Anaerobic Speed Reserve Domain: The Untapped Tools that Differentiate the World's Best Male 800 m Runners. *Sports Medicine*. 2019;49(6):843-852. doi:10.1007/s40279-018-1010-5
118. Sandford GN, Rogers SA, Sharma AP, Kilding AE, Ross A, Laursen PB. Implementing anaerobic speed reserve testing in the field: Validation of vVO2max prediction from 1500-m race performance in elite middle-distance runners. *International Journal of Sports Physiology and Performance*. 2019;14(8):1147-1150. doi:10.1123/ijspp.2018-0553
119. Duffield R, Dawson B. Energy system contribution in track running. In: IAAF New Studies in Athletics; 2003.
120. Rønnestad BR, Hansen J, Nygaard H, Lundby C. Superior performance improvements in elite cyclists following short-interval vs effort-matched long-interval training. *Scandinavian Journal of Medicine and Science in Sports*. 2020;30(5):849-857. doi:10.1111/sms.13627
121. Jones AM. A five year physiological case study of an Olympic runner. *British Journal of Sports Medicine*. 1998;32(1):39-43. doi:10.1136/bjsm.32.1.39
122. Coyle EF. Improved muscular efficiency displayed as Tour de France champion matures. *Journal of Applied Physiology*. 2005;98(6):2191-2196. doi:10.1152/japplphysiol.00216.2005
123. Sylta Ø, Tønnessen E, Hammarström D, et al. The Effect of Different High-Intensity Periodization Models on Endurance Adaptations. *Medicine & Science in Sports & Exercise*. 2016;48(11):2165-2174. doi:10.1249/MSS.0000000000001007
124. Sellés Pérez S, Fernández-Sáez J, Cejuela R. Polarized and pyramidal training intensity distribution: Relationship with a half-ironman distance triathlon competition. *Journal of Sports Science and Medicine*. 2019;18(4):708-715.
125. Muñoz I, Cejuela R, Seiler S, Larumbe E, Esteve-Lanao J. Training-Intensity Distribution During an Ironman Season: Relationship With Competition Performance. *International Journal of Sports Physiology and Performance*. 2014;9(2):332-339. doi:10.1123/ijspp.2012-0352
126. Manunzio C, Mester J, Kaiser W, Wahl P. Training Intensity Distribution and Changes in Performance and Physiology of a 2nd Place Finisher Team of the Race across America Over a 6 Month Preparation Period. *Frontiers in Physiology*. 2016;7. doi:10.3389/fphys.2016.00642
127. Joyner MJ, Ruiz JR, Lucia A. The two-hour marathon: who and when? *Journal of Applied Physiology*. 2011;110(1):275-277. doi:10.1152/japplphysiol.00563.2010
128. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *The Journal of Physiology*. 2008;586(1):35-44. doi:10.1113/jphysiol.2007.143834
129. Joyner MJ. Modeling: optimal marathon performance on the basis of physiological factors. *Journal of Applied Physiology*. 1991;70(2):683-687. doi:10.1152/jappl.1991.70.2.683

130. Billat V, Pycke JR, Vitiello D, Palacin F, Correa M. Race analysis of the world's best female and male marathon runners. *International Journal of Environmental Research and Public Health*. 2020;17(4). doi:10.3390/ijerph17041177
131. Casado A, González-Mohíno F, González-Ravé JM, Boullosa D. Pacing Profiles of Middle-Distance Running World Records in Men and Women. *International Journal of Environmental Research and Public Health*. 2021;18(23):12589. doi:10.3390/ijerph182312589
132. Díaz JJ, Fernández-Ozcorta EJ, Santos-Concejero J. The influence of pacing strategy on marathon world records. *European Journal of Sport Science*. 2018;18(6):781-786. doi:10.1080/17461391.2018.1450899
133. Maunder E, Seiler S, Mildenhall MJ, Kilding AE, Plews DJ. The Importance of 'Durability' in the Physiological Profiling of Endurance Athletes. *Sports Medicine*. 2021;51(8):1619-1628. doi:10.1007/s40279-021-01459-0
134. Muriel X, Mateo-March M, Valenzuela PL, et al. Durability and repeatability of professional cyclists during a Grand Tour. *European Journal of Sport Science*. Published online October 24, 2021:1-8. doi:10.1080/17461391.2021.1987528
135. Boullosa D, Esteve-Lanao J, Casado A, Peyré-Tartaruga LA, Gomes da Rosa R, del Coso J. Factors Affecting Training and Physical Performance in Recreational Endurance Runners. *Sports*. 2020;8(3):35. doi:10.3390/sports8030035
136. Coquart JBJ, Alberty M, Bosquet L. Validity of a Nomogram to Predict Long Distance Running Performance. *Journal of Strength and Conditioning Research*. 2009;23(7):2119-2123. doi:10.1519/JSC.0b013e3181b3dcc3
137. Mercier D, Leger L, Desjardins M. Nomogramme puor predire la performance le VO2 max. et l'endurance relative en course de fond. *Medecine du Sport*. 1984;4.
138. Gamelin FX, Coquart J, Ferrari N, et al. Prediction of One-Hour Running Performance Using Constant Duration Tests. *The Journal of Strength and Conditioning Research*. 2006;20(4):735. doi:10.1519/R-17905.1
139. Ingham SA, Whyte GP, Pedlar C, Bailey DM, Dunman N, Nevill AM. Determinants of 800-m and 1500-m Running Performance Using Allometric Models. *Medicine & Science in Sports & Exercise*. 2008;40(2):345-350. doi:10.1249/mss.0b013e31815a83dc
140. Zrenner M, Heyde C, Duemler B, Dykman S, Roecker K, Eskofier BM. Retrospective Analysis of Training and Its Response in Marathon Finishers Based on Fitness App Data. *Frontiers in Physiology*. 2021;12. doi:10.3389/fphys.2021.669884
141. Alvero-Cruz J, Carnero E, García M, et al. Predictive Performance Models in Long-Distance Runners: A Narrative Review. *International Journal of Environmental Research and Public Health*. 2020;17(21):8289. doi:10.3390/ijerph17218289
142. Haugen T, Sandbakk Ø, Seiler S, Tønnessen E. The Training Characteristics of World-Class Distance Runners: An Integration of Scientific Literature and Results-Proven Practice. *Sports Medicine - Open*. 2022;8(1):46. doi:10.1186/s40798-022-00438-7
143. 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. *International Journal of Sports Physiology and Performance*. Published online 2022:1-14. doi:10.1123/ijspp.2021-0435

144. Boullosa DA, Abreu L, Varela-Sanz A, Mujika I. Do Olympic Athletes Train as in the Paleolithic Era? *Sports Medicine*. 2013;43(10):909-917. doi:10.1007/s40279-013-0086-1
145. Bourgois JG, Bourgois G, Boone J. Perspectives and Determinants for Training-Intensity Distribution in Elite Endurance Athletes. *International Journal of Sports Physiology and Performance*. 2019;14(8):1151-1156. doi:10.1123/ijspp.2018-0722
146. van Cutsem J, Marcora S, de Pauw K, Bailey S, Meeusen R, Roelands B. The Effects of Mental Fatigue on Physical Performance: A Systematic Review. *Sports Medicine*. 2017;47(8):1569-1588. doi:10.1007/s40279-016-0672-0
147. Taylor IM, Whiteley S, Ferguson RA. Disturbance of desire-goal motivational dynamics during different exercise intensity domains. *Scandinavian Journal of Medicine & Science in Sports*. Published online January 27, 2022. doi:10.1111/sms.14129
148. Casado A, Hanley B, Santos-Concejero J, Ruiz-Pérez LM. World-Class Long-Distance Running Performances Are Best Predicted by Volume of Easy Runs and Deliberate Practice of Short-Interval and Tempo Runs. *Journal of Strength and Conditioning Research*. 2021;35(9):2525-2531. doi:10.1519/JSC.0000000000003176
149. Campos Y, Casado A, Vieira JG, et al. Training-intensity Distribution on Middle- and Long-distance Runners: A Systematic Review. *International Journal of Sports Medicine*. 2022;43(04):305-316. doi:10.1055/a-1559-3623

9

ADDENDUMS

'If you work hard, follow what's required and set your priorities right,
then you can really perform without taking shortcuts.
If you're taking shortcuts, you can't be free.'

Eliud Kipchoge

Study 1

<u>Kenneally M</u>, Casado A, Santos-Concejero J. The Effect of Periodisation and Training Intensity Distribution on Middle and Long-Distance Running Performance: A Systematic Review. *Int J Sports Physiol Perform* 13(9):1114-21. 2018

Quality indicators: ISI-JCR Impact factor: 3.979. 8/83 (Q1) SPORT SCIENCES 2018

***International Journal of Sports Physiology and Performance*, 2018, 13, 1114-1121**
https://doi.org/10.1123/ijspp.2017-0327

Human Kinetics
BRIEF REVIEW

The Effect of Periodization and Training Intensity Distribution on Middle- and Long-Distance Running Performance: A Systematic Review

Mark Kenneally, Arturo Casado, and Jordan Santos-Concejero

This review aimed to examine the current evidence for 3 primary training intensity distribution types: (1) pyramidal training, (2) polarized training, and (3) threshold training. Where possible, the training intensity zones relative to the goal race pace, rather than physiological or subjective variables, were calculated. Three electronic databases (PubMed, Scopus, and Web of Science) were searched in May 2017 for original research articles. After analysis of 493 resultant original articles, studies were included if they met the following criteria: (1) Their participants were middle- or long-distance runners; (2) they analyzed training intensity distribution in the form of observational reports, case studies, or interventions; (3) they were published in peer-reviewed journals; and (4) they analyzed training programs with a duration of 4 wk or longer. Sixteen studies met the inclusion criteria, which included 6 observational reports, 3 case studies, 6 interventions, and 1 review. According to the results of this analysis, pyramidal and polarized training are more effective than threshold training, although the latest is used by some of the best marathon runners in the world. Despite this apparent contradictory finding, this review presents evidence for the organization of training into zones based on a percentage of goal race pace, which allows for different periodization types to be compatible. This approach requires further development to assess whether specific percentages above and below race pace are key to inducing optimal changes.

Keywords: polarized training, pyramidal training, threshold training, race pace, training program

Endurance training involves manipulation of intensity, duration, and frequency of training sessions.[1] The precise detail of this "manipulation," however, remains an area of debate across the literature. To further guide understanding of this area, different training intensity zones have been described, determined by either physiological factors (ie, lactate threshold [LT], ventilatory threshold [VT], percentage of the maximum oxygen uptake [%VO_2max], percentage of the maximum heart rate [%HRmax]) or subjective factors (ie, session goal or session rate of perceived exertion [RPE-Borg scale]).[2]

Three training intensity zones of endurance athletes are most commonly used in the literature[1,3] and are considered similar regardless of the method used to determine them. However, up to 7 intensity zones can be also used to describe the training intensity distribution (TID).[4] Both TID and periodization of training volume and intensity are traditionally considered to be important factors in the design of a training program for endurance running performance.[5]

There appears to be a longstanding consensus in the literature regarding factors that limit such performance, namely VO_2max,[6] VO_2max,[7] LT,[7,8] and running economy,[9] and on how these factors could be improved by using different training intensity procedures. However, a disparate number of TIDs are employed in practice.[10] Three primary TIDs are recognized in this review: (1) the traditional pyramidal approach, in which decreasing volume of running is performed in zones 1, 2, and 3, respectively. Typically[11] this has been described as comprising 80% in zone 1, with the remaining 20% split between zones 2 and 3 decreasing sequentially; (2) polarized training, in which relatively high volumes of training are performed in zone 1 (~80%) and zone 3 (20%), with little or none in zone 2[11]; and (3) threshold training, in which higher volumes (>20%) of running are performed in zone 2 than other models.[11] Previous research has identified pyramidal training as the primary TID employed by well-trained and elite endurance athletes, noting that "some world-class athletes adopt a so-called 'polarized' TID during certain phases of the season."[3]

This observation has been supported by an observational review[12] detailing the training of international-level-distance runners, which notes the emphasis on relatively high volume–low intensity in the training of athletes specializing in distances from 1500 m to marathon. However, a training manual published by the International Association of Athletics Federation based on the work of Renato Canova (the coach of some of the fastest Kenyan marathon runners in recent times, including world record holders) has demonstrated a tendency toward a threshold-oriented TID.[13] Seiler and Tonnessen[1] argue the case for an 80:20 distribution ratio between high- and low-intensity work based on observational reports describing the training of elite endurance athletes. These authors recognize both pyramidal and polarized models of TID as being most common in these athletes.[1]

It is against this apparently contradictory background that this review intends to examine the current literature specifically for endurance running, and subsequently to analyze the available data, where possible, by determining intensity zones relative to the goal race pace in different distances, rather than physiological or subjective variables.

Methods

Experimental Approach to the Problem

A literature search was conducted on May 6, 2017, and the following databases were searched: PubMed, Scopus, and Web of

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Science. Databases were searched from inception up to May 2017, with no language limitation. Citations from scientific conferences were excluded.

Literature Search

In each database, the title, abstract, and keywords search fields were searched. The following keywords, combined with Boolean operators (AND, OR), were used: "training intensity distribution running," "periodisation running," "training intensity distribution endurance," "periodisation endurance," "polarised training running," "pyramidal training running," and "threshold training running." No additional filters or search limitations were used.

Inclusion Criteria

Studies were eligible for further analysis if the following inclusion criteria were met: (1) participants were middle- or long-distance runners (studies with triathletes or any other kind of athletes were excluded); (2) studies analyzed TID and/or periodization in the form of observational reports, case studies, or interventions; (3) studies published in peer-reviewed journals; and (4) studies analyzed training programs with a duration of 4 weeks or longer.

Two independent observers reviewed the studies and then individually decided whether inclusion was appropriate. In the event of a disagreement, a third observer was consulted to determine the inclusion of the study. A flowchart of the search strategy and study selection is shown in Figure 1.

Quality Assessment

Oxford's level of evidence[14] and the physiotherapy evidence database (PEDro) scale[15] were used by 2 independent observers to assess the methodological quality of the articles included in the review. Oxford's level of evidence ranges from 1a to 5, with 1a being systematic reviews of high-quality randomized controlled trials and 5 being the expert opinions. The PEDro scale consists of 11 different items related to scientific rigor. The items include random allocation; concealment of allocation; comparability of groups at baseline; blinding of subjects, researchers, and assessors; analysis by intention to treat; and adequacy of follow-up. Items 2 to 11 can be rated with 0 or 1, so the highest rate in the PEDro scale is 10, and the lowest is 0. Zero points are awarded to a study that fails to satisfy any of the included items and 10 points to a study that satisfies all the included items.

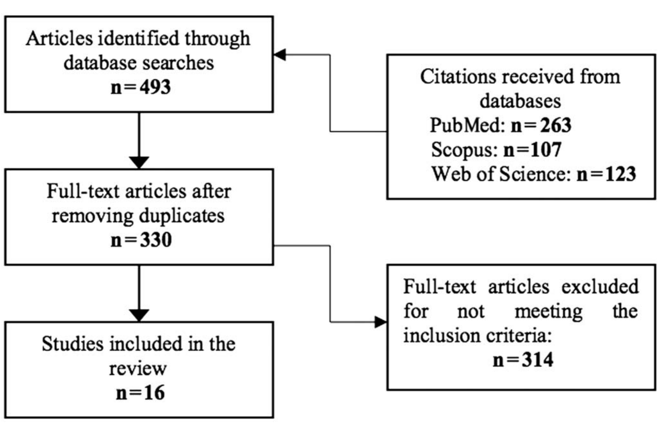

Figure 1 — Flowchart of search strategy and selection of articles.

Statistical Analysis

All values are expressed as mean (SD). In studies with sufficient data, TID determined by traditional physiological parameters was compared with a race-pace-based TID using a Cohen's *d*.[16] Training zones for the race-pace approach were determined as follows: zone 1, volume performed at <95% of goal race pace; zone 2, volume performed between 95% and 105% of goal race pace; and zone 3, volume performed at >105% of goal race pace. The magnitude of differences or effect size (ES) of this comparison was interpreted as small (>0.2 and <0.6), moderate (≥0.6 and <1.2), large (≥1.2 and <2.0), and very large (≥2.0) according to the scale proposed by Hopkins et al.[17]

Results

Studies Selected

The search strategy yielded 493 total citations, presented in Figure 1. After removing 163 duplicates and reviewing the resultant 330 full-text articles, only 16 studies met the inclusion criteria. Excluded studies had at least one of the following characteristics: participants were not middle- or long-distance runners and intervention/observation period lasted <4 weeks. The overall sample included 6 observational reports, 3 case studies, and 6 interventions. One review was also included (Table 1).

Level of Evidence and Quality of the Studies

Of the 16 included studies, 4 studies had a level of evidence 1c (high-quality randomized controlled trial). The remaining 12 studies had a level of evidence 2c or less as participants were not randomly allocated into the intervention or control groups. Also, the mean score in the PEDro scale was 3.75 (1.9), with values ranging from 1 to 6 (Table 2).

Characteristics of the Participants

Participants were characterized as recreational or high-level athletes, with delineation defined by whether the athletes competed internationally. A summary of participants' characteristics is presented in Table 1. The total number of participants was 215 (194 men and 21 women) with an age ranging from 17 to 51 years.

Evidence for a Pyramidal TID

Four interventional studies that support the use of a pyramidal TID exist: Esteve-Lanao et al,[22] Clemente-Suarez and Gonzalez-Rave,[29] Manzi et al,[30] and Clemente-Suarez et al.[31] Similarly, 4 observational reports[4,18,21,23] and 2 case studies[26,28] confirm the use of pyramidal training in elite and well-trained runners.

Esteve-Lanao et al[22] examined the effect of decreasing volume of training performed at threshold intensity on running performance in 12 male subelite endurance runners while maintaining equal volumes of high-intensity work between 2 groups (threshold and pyramidal training groups; Figure 2). Running performance was assessed by a simulated 10.4-km cross-country (XC) race assessed before and after the 5-month intervention period. The pyramidal group displayed a significantly better improvement in performance than the threshold group. The TID in both threshold (Figure 2A) and pyramidal groups (Figure 2B) was different from a race-pace-based TID (Figure 2; ES > 2.0, very large effect). It

Table 1 Characteristics of the Studies and the Participants

	Participants		Study	
Study	**N (M/F)**	**Age, y**	**Level**	**Main outcome**
Robinson et al[18]	13 (13/0)	26.1 (4.7)	Elite	TID
Billat et al[19]	20 (10/10)	–	Elite	Physiology
Billat et al[20]	20 (13/7)	–	Elite	TID
Esteve-Lanao et al[21]	8 (8/0)	23 (2)	Well trained	TID
Esteve-Lanao et al[22]	20 (20/0)	27 (2)	Well trained	Race performance
Tjelta and Enoksen[23]	4 (4/0)	17.8 (1)	Elite	TID and race performance
Enoksen et al[4]	6 (3/3)	Not specified	Elite	TID and race performance
Stellingwerff[24]	3 (3/0)	28.3 (2.3)	Elite	TID
Ingham et al[25]	1 (M)	26	Elite	TID and race performance
Tjelta[26]	1 (M)	20–21	Elite	TID and race performance
Stöggl and Sperlich[10]	21 (not specified)	31 (6)	Well trained	Physiology
Muñoz et al[27]	30 (not specified)	34 (9)	Recreational	Race performance
Tjelta et al[28]	1 (F)	25/26	Elite	TID
Clemente-Suarez and Gonzalez-Rave[29]	30 (30/0)	38.7 (9.8)	Well trained	Aerobic performance
Manzi et al[30]	7 (7/0)	36.5 (3.8)	Recreational	TID and race performance
Clemente-Suarez et al[31]	30 (30/0)	38.7 (9.8)	Recreational	Physiology and performance
Tjelta[12]	56 (34/22)	Not specified	Elite	TID

Abbreviations: M/F, male/female; TID, training intensity distribution.

Table 2 PEDro Ratings and Oxford Evidence Levels of the Included Studies

	PEDro ratings												
Study	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**	**Evidence level**
Robinson et al[18]	No	0	0	0	0	0	0	1	0	0	0	1	4
Billat et al[19]	Yes	0	0	1	0	0	0	1	1	0	1	4	4
Billat et al[20]	Yes	0	0	1	0	0	0	1	1	1	1	5	4
Esteve-Lanao et al[22]	Yes	1	0	1	0	0	0	1	1	1	1	6	4
Tjelta and Enoksen[23]	No	0	0	0	0	0	0	0	1	1	0	2	4
Enoksen et al[4]	No	0	0	1	0	0	0	0	0	0	0	1	4
Stellingwerff[24]	No	0	0	1	0	0	0	0	0	1	1	3	4
Ingham et al[25]	No	0	0	1	0	0	0	0	0	1	1	3	3b
Tjelta[26]	No	0	0	0	0	0	0	0	1	1	0	2	4
Stöggl and Sperlich[10]	Yes	1	0	1	0	0	0	1	1	1	1	6	1c
Muñoz et al[27]	Yes	1	0	1	0	0	0	1	1	1	1	6	1c
Tjelta et al[28]	No	0	0	0	0	0	0	0	1	1	0	2	4
Clemente-Suarez and Gonzalez-Rave[29]	Yes	1	0	1	0	0	0	1	1	1	1	6	1c
Manzi et al[30]	Yes	0	0	1	0	0	0	1	1	1	1	5	2c
Clemente-Suarez et al[31]	Yes	1	0	1	0	0	0	1	1	1	1	6	1c
Tjelta[12]	No	0	0	0	0	0	0	0	1	1	0	2	3a

Abbreviation: PEDro, Physiotherapy Evidence Database. Note: Items in the PEDro scale: 1 = eligibility criteria were specified; 2 = subjects were randomly allocated to groups; 3 = allocation was concealed; 4 = the groups were similar at baseline regarding the most important prognostic indicators; 5 = blinding of all subjects; 6 = blinding of all therapists who administered the therapy; 7 = blinding of all assessors who measured at least 1 key outcome; 8 = measures of 1 key outcome were obtained from 85% of subjects initially allocated to groups; 9 = all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least 1 key outcome were analyzed by "intention to treat"; 10 = the results of between-group statistical comparisons are reported for at least 1 key outcome; 11 = the study provides both point measures and measures of variability for at least 1 key outcome.

should be noted that zone 3 can only be considered a subset of zone 2 in this analysis as details of the zone 3 training are not provided but are equal between groups.

Clemente-Suarez and Gonzalez-Rave[29] examined the effect of applying a pyramidal TID over a 4-week time period to 30 recreational athletes. One group (constant) maintained a constant weekly training load in terms of volume and intensity, whereas another group had an increasing proportion of higher intensity work, week by week over the 4 weeks. The final group was free to train as they wished. Total training volume for the 4 weeks was

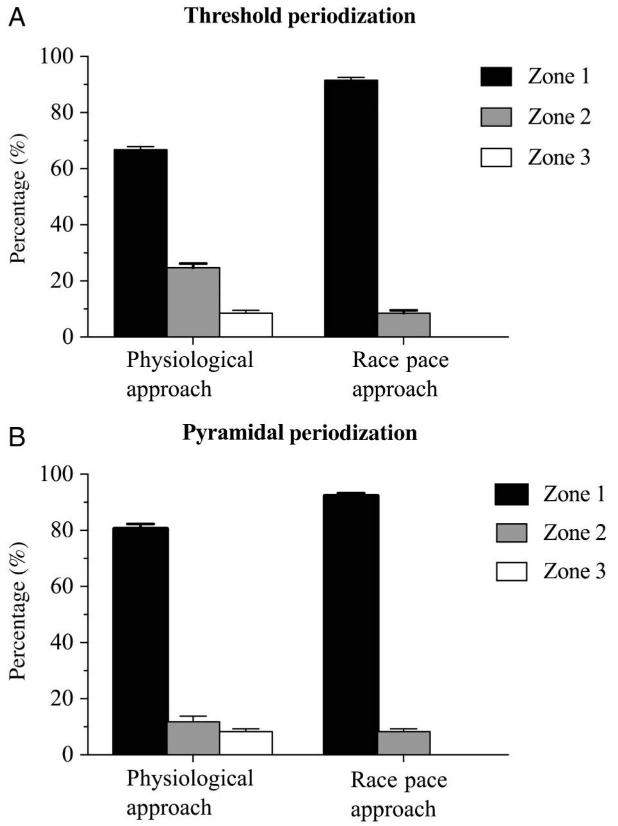

Figure 2 — Comparison of training intensity distribution between a physiological and a race-pace-based approached in (A) threshold periodization and (B) pyramidal periodization groups. Data from Esteve-Lanao et al.[22]

recorded by time (in minutes). The constant group completed 1051 (11) minutes, the increasing group completed 1105 (1.3) minutes, and the free group completed 1512 (67.6) minutes. The stated goal of the 4-week time period was to develop "aerobic endurance." No race distance or performance was specified, rather the changes were measured via laboratory testing. No significant performance differences existed between groups poststudy, although the groups did exhibit different physiological changes over the 4 weeks. Clemente-Suarez et al,[31] using data from the previously mentioned study, found that the group with increasing intensity over the 4 weeks had a significantly better running velocity at 8 mmol·L^{-1} at midcondition and postcondition. No time trial or race performance data for the groups were provided, so it was not possible to examine the TIDs in this method.

Manzi et al[30] assessed the TID of 7 recreational marathon runners in the preparation phase of a marathon training cycle. Interestingly, when their training (which was pyramidal in nature according to their baseline physiological testing) was assessed against their eventual race pace, it appeared to be a polarized-type TID (Figure 3; ES > 2.0, very large effect).

Robinson et al[18] analyzed 13 national ranked male New Zealand distance runners' training during the "build-up" phase of their season and identified 2 training zones according to blood lactate: above LT (4 mmol·L^{-1}) or below LT. Training during this period was described as 96% below LT and 4% above LT.

Tjelta and Enoksen[23] described the training of a group of 4 top-level male junior XC runners over the course of a season. Five

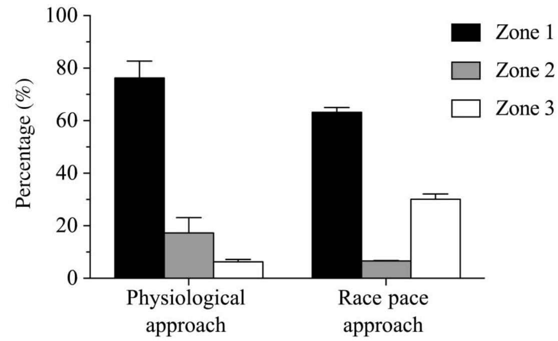

Figure 3 — Comparison of training intensity distribution between a physiological and a race-pace-based approach in a pyramidal periodization group. Training zones for the physiological approach were described as following: zone 1, <2 mmol·L^{-1} of lactate; zone 2, between 2 and 4 mmol·L^{-1} of lactate; zone 3, >4 mmol·L^{-1} of lactate. Data from Manzi et al.[30]

training zones based on HR and blood lactate were used to describe the TID, and training was divided into 3 seasons: base, track, and XC. The training in this study can be described as traditionally pyramidal in distribution, with 78%, 81%, and 78% of the training volume having been carried out in the low-intensity zone 1 in base, track, and XC seasons, respectively. Race intensity for these athletes across the whole season was zone 3 (10 km and 3 km), with some zone 4 (1500 m) races during the track season. Training intensification (training phases closer to competition) is characterized by an increase in the volume just below, up to, and over race pace (zones 3 and 4). In this study, when TID was calculated according to race pace, the volume of training performed above race pace was similar to other studies using either pyramidal or polarized methods.[4,20,28,30]

Enoksen et al[4] analyzed 6 top international Norwegian marathon and track distance runners' training in a subsequent study. Seven training zones were identified and used to determine the TIDs. The marathon runners performed a relatively high proportion of their training at zone 2 (equivalent of marathon pace) and zone 4 (10-km pace) in their base and precompetition phase with nothing at zone 3 (half-marathon pace), and then in competition phase, nothing at zone 4 and an increase in the volume at zone 3, whereas maintaining a relatively high proportion at zone 2. The track runners (who competed over 5 km) completed relatively high volumes at zones 2 and 3 in all phases. However, the volume in zone 3 dropped and zone 5 (3-km and 5-km race pace) increased in the competition phase. They had minimal volume in zone 4 (10-km pace) across all phases.

Esteve-Lanao et al[21] described the training of 8 regional and national class Spanish runners, using 3 intensity zones: up to VT_1, between VT_1 and VT_2, and above VT_2, and similarly described a pyramidal distribution (71% in zone 1, 21% in zone 2, and 8% in zone 3).

Tjelta[26] analyzed the training of the 2012 European 1500-m champion over 4 years and noted a pyramidal distribution over the time period, at all times of the season despite some variation corresponding to the periodization of the athletes training. Five intensity zones were described relative to blood lactate, %HRmax, and intended physiological adaptation, and during all phases of training, the maintenance of a relatively high volume in zone 2 (threshold training) was observed. This does reduce closer to the competitive season, but it still constitutes a larger proportion of training than zones 3, 4, or 5 at all time points.

Similarly, the training of 9-times New York marathon winner Grete Waitz was also reported as pyramidal at all time points across a 2-year time period.[28] The periodization identified 7 intensity zones and a decreasing volume of work done at increasing intensity levels was observed.

Evidence for a Polarized TID

Two interventional studies exist, which support the use of a polarized TID: Muñoz et al[27] and Stöggl and Sperlich.[3] Both studies defined 3 intensity zones relative to physiological characteristics. Similarly, 3 observational reports[19,20,24] and 1 case study[25] confirm the use of polarized training in elite, well-trained, and recreational athletes.

Muñoz et al[27] quantified the impact of TID on 10-km race performance in 30 recreational athletes. Two groups, emphasizing polarized- or threshold-type training, were examined. Both groups improved over a 10-week intervention period although the polarized group exhibited a better improvement over 10-km race distance than the threshold group (5.0% vs 3.6%, nonsignificant). Both groups completed an 8-week standard training program prior to the study, which was pyramidal in TID. In this study, both groups spent the same absolute amount of time in zone 3 with the polarized group zone 1 (Figure 4A) and the threshold group emphasizing zone 2 (Figure 4B). The actual completed training

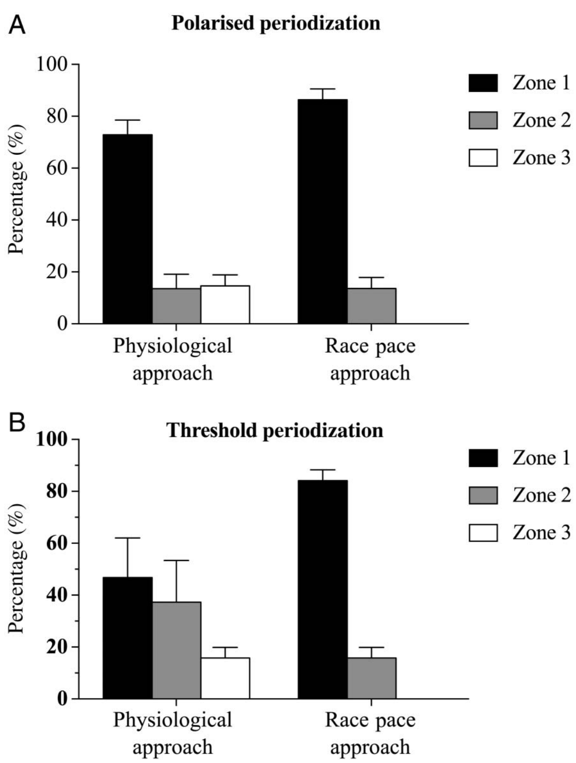

Figure 4 — Comparison of training intensity distribution between a physiological and a race-pace-based approach in (A) polarized periodization and (B) threshold periodization groups. Training zones for the physiological approach were described as following: zone 1, < VT; zone 2, between VT and the RCP; zone 3, > RCP. Data from Muñoz et al.[27] RCP indicates respiratory compensation point; VT, ventilatory threshold.

of the polarized group was not a truly polarized TID as the authors intended that this group would complete only 5.0% of the training in zone 2, rather than the 13.5% finally completed. The TID in both polarized (Figure 4A) and threshold groups (Figure 4B) was different from a race-pace-based TID (Figure 4; ES > 2.0, very large effect).

Stöggl and Sperlich[3] examined 48 athletes, 21 of whom were national-level runners, in their randomized controlled trial comparing 4 different TIDs over a 9-week period. The TIDs were high volume, threshold, high-intensity interval training, and polarized. Polarized training resulted in the greatest improvement of the variables examined (VO_2max, peak velocity, and time to exhaustion on a ramp protocol). A time trial or race performance was not performed to allow analysis of race-pace zones based on this.

Billat et al[19] compared top-class male Portuguese and French marathon runners to their "high-level" counterparts (as defined by a marathon time of 2:12). They described high volumes of polarized training. Their zones were defined, however, by marathon race pace. Zone 1 was described as < marathon pace, zone 2 = marathon pace, zone 3 > marathon pace, a definition not replicated anywhere else in the literature and no specification of the tolerance around marathon pace for each zone is provided. The same authors also described the training of Kenyan distance runners (10-km specialists) and described 2 main TID types[20]: high-volume low-intensity and low-volume high-intensity. In the group studied, there were 13 men (6 high-intensity type and 7 low-intensity type) and 7 women (6 high-intensity type and 1 high-intensity type). The lower volume athletes in this study tended to perform more of their training in zones 4 and 5 (4.3% and 5.0%, respectively) than their high-volume counterparts, who only performed 1.4% of their volume in zones 4 and 5 combined, with 14.4% in zone 3.

Stellingwerff[24] described the training of 3 Canadian international marathon runners over a 16-week period before a marathon race. The intensity zones were defined subjectively by rate of perceived exertion as zone 1 (easy to somewhat hard), zone 2 ("threshold"), and zone 3 (very hard to maximal). A polarized distribution was described in which 74%, 11%, and 15% of training sessions were performed in zones 1, 2, and 3, respectively.

Ingham et al[25] presented the case study of an international 1500-m runner, who improved his personal best from 3:38.9 to 3:32.4 over a two 2-year period. The analysis of his training showed a reduction in training volume performed between 80% and 90% VO_2max from 42% to 20% and between 90% and 100% from 20% to 10%. At the same time, low-intensity training volume (<80% VO_2max increased from 20% to 55% and training volume at 100%–130% VO_2max increased from 7% to 10%), thus emphasizing a shift toward a more polarized TID. Note that these numbers are approximate as the information is only provided graphically in the article and that 1500-m race falls at approximately 110% VO_2max.

Discussion

According to the results of this review, there is a clear dichotomous evidence base with regard to TID in the literature. The overwhelming evidence describes 2 main strands: pyramidal and polarized training.

Contemporary endurance training has developed, from a historical perspective, from coaches like Arthur Lydiard, who used pyramidal TIDs to coach successful athletes.[12] The more recent move toward polarized-type TIDs has emerged as the scientific evaluation of endurance performance has identified key determinants of endurance performance and methods by which to improve these determinants.[32] However, the precise nature of the interaction of these determinants and the effect of that interaction remain elusive.

For example, although LT is recognized as one of the key determinants of endurance performance,[8] threshold-type training is considered to be more demanding than other TIDs (ie, pyramidal and polarized), potentially because of effects on the autonomic and endocrine systems, or on the lactate/power profile.[27] When threshold training has been compared in this regard in the literature, it consistently proves to be less effective in the studies available. Yet, there is anecdotal evidence, at the very highest level, of the use of threshold training in structuring world-best marathon performances.

The coach of a number of world-class Kenyan athletes has written a marathon training manual for the International Association of Athletics Federation[13] and has made publicly available the training programs of his athletes. These programs repeatedly show the use of high volumes (ie, differing from the traditional 80:20 approach) of training in the threshold zone (as defined by $\%VO_2max$, assuming 100% of VO_2max corresponds to ~3000-m pace). The coach (Renato Canova) describes this training as specific race pace.

The periodization employed, however, demonstrates an initial block of polarized training, emphasizing high and low intensity, leading into a specific preparatory phase, which is threshold-oriented, thereby employing both of the main TIDs described at different phases of training, according to the intended goal of the phase.[13] So, in the specific example, marathon pace lies in the threshold zone, so a relatively large volume of training is performed in this physiological zone as the date of a specific race approaches. The volume of training performed around race pace seems to be dictated by the distance of the impending race, with shorter races, requiring faster paces, seeing less volume, and longer races requiring increasing volumes in around race pace.

Thus, the dichotomous approach described previously may be flawed in its inception. It may prove more valuable in future studies to examine the precise physiological characteristics associated with optimal race performance and how these physiological characteristics change with different TID approaches. Similarly, different approaches may prove valuable at different phases and for approaching different races.[27] In this way, the training may be organized in the early parts according to physiological characteristics such as HR or lactate profile, but as the race date approaches, training becomes more pragmatic and focuses on running at and around specific race pace, regardless of what is happening to physiological measurable.[23,28] This represents a way of incorporating the scientific principles, which are fairly well established as being important for specific race distance performance, while also being cognizant of the fact that the literature is deficient in describing an optimal TID and periodization strategy, based on good evidence.[12]

It is well established that from races as short as 1500 m, the aerobic system is the main contributor of energy (85%)[33] so the TIDs seen reflect that, as no matter what TID is examined, zone 1 is always the highest proportion. However, when comparing physiological-based intensity zones and race-pace-based intensity zones, it seems from the data assessed in this review that race pace may be a larger factor in the design of training programs than physiological variables. This may be a coaching flaw, but the interesting similarity in the TIDs when analyzed by a race-pace-based approach at least warrants some attention as these are data from successful athletes. As discussed earlier, no optimal TID has been well established, and similarly, no optimal numbers for the physiological determinants (VO_2max, VO_2max, running economy, and LT) of middle- and long-distance running to predict performance exist.[2] The interaction between these variables is the key to endurance running, and it may be possible that race-pace-based training provides the perfect stimulus for their concurrent development. As previously described, training aimed at improving threshold seems to limit the development of VO_2max.[3] However, as Coyle and Krauenbuhl[7] showed, large variation in laboratory endurance performance is explained by the $\%VO_2max$, which can be utilized at threshold, so this limitation may not be a hindrance to performance. The specificity of intention may be more important.

Race-pace-based zones may also reflect the fact that races in an endurance running competition are directly comparable because of the similarity of courses and the validity of time comparison on different courses. Other endurance sports, such as road cycling, rowing, or XC skiing, which have been examined in the literature on TID[11,34] do not share this same capacity for direct competition to competition comparison of speed because of the nature of different courses characteristics (ie, profile, altitude, and so on). Training organized therefore based on physiological characteristics for these sports is the norm. No study in these sports, to the authors' best knowledge, has reported a polarized TID based on zones that are externally defined (ie, power or speed).

This dichotomy between measuring and monitoring workload internally (physiologically guided) versus externally (eg, pace guided) has been explored in 2 recent reviews: Foster et al[35] and Mujika.[32] Foster et al[35] outline the practical difficulties of accurately monitoring internal workload/physiological parameters, which they note are lessening. Nonetheless, such practical difficulties should not affect the development of theoretical principles based on physiological measures (eg, running economy, VO_2max, and LT), should an integrated approach to their concurrent development become evident.

Further studies analyzing the behavior of physiological characteristics such as HR response, top speed, and lactate profile at different phases of a season and also how they change in the short and medium term in response to training are thus warranted. Comparison of these measures to race performance, along with physiological profiling compared with performance, may also allow a better understanding of the interactions between physiological characteristics and the impact of these interactions on performance. This may allow for better individualized planning and prescription of training, which is founded on evidence rather than anecdote/tradition.

Conclusions

Current evidence describes pyramidal and polarized training as more effective than threshold training, although the latest is used by some of the best marathon and distance runners in the world. Despite the apparent contradictory evidence on TID and periodization, an approach based on race pace has been suggested in this review, which may allow for different TID types to be compatible. It is suggested that this may be unique to endurance running because of the standardization of race distances and courses. A race-pace-based TID recognizes the traditional high volume of low-intensity training associated with endurance training, but presents evidence (when analyzed retrospectively) for the organization of high-intensity training into zones based on a percentage of race pace, rather than physiological zones, which appears to be relatively consistent across distances. A training session at a given percentage of race pace for a longer event is naturally going to be slower, in absolute terms, than a session at the same percentage of race pace for a middle-distance event. Therefore, these 2 sessions may fall into completely different physiological zones, yet it may serve the same purpose from a session intention perspective. The requirement to sustain a particular pace obviously also differs by race distance, and in this way, the volume of these sessions will also differ longer races requiring longer sessions etc, which may also affect analysis via a physiological-only approach. Tjelta et al[23,28] recognize the relationship between race pace and physiology and display race pace alongside physiological zones as a secondary zone target. This approach requires further development to assess whether specific percentages above and below race pace are key to inducing optimal changes, and whether, as has been questioned previously, the potential concurrent development of relevant physiological characteristics is indeed a factor. Such an approach throws more questions about the nature of endurance running performance but may help to guide experimental inquiries into this performance along a slightly different path than currently being tread.

References

1. Seiler S, Tonnessen E. Intervals, threshold and long slow distance: the role of intensity and duration in endurance training. *Sports Sci*. 2009;13:32–53.
2. Seiler S, Kjerland GO. Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? *Scand J Med Sci Sports*. 2006;16:49–56. PubMed ID: 16430681 doi:10.1111/j.1600-0838.2004.00418.x
3. Stöggl TL, Sperlich B. The training intensity distribution among well-trained and elite endurance athletes. *Front Physiol*. 2015;6:295. PubMed ID: 26578968 doi:10.3389/fphys.2015.00295
4. Enoksen E, Tjelta AR, Tjelta LI. Distribution of training volume and intensity of elite male and female track and marathon runners. *Int J Sports Sci Coach*. 2011;6: 273–293. doi:10.1260/1747-9541.6.2.273
5. Faulkner JA. New perspectives in training for maximum performance. *JAMA*. 1968;205:741–746. PubMed ID: 5695282 doi:10.1001/jama.1968.03140370043009
6. McLaughlin JE, Howley ET, Bassett DR, Thompson DL, Fitzhugh EC. Test of the classic model for predicting endurance running performance. *Med Sci Sports Exerc*. 2010; 42(5):991–997. PubMed ID: 19997010 doi:10.1249/MSS.0b013e3181c0669d
7. Coyle EF. Integration of the physiological factors determining endurance performance ability. *Exerc Sports Sci Rev*. 1995;23:25–63. PubMed ID: 7556353
8. Allen WK, Seals DR, Hurley BF, Ehsani AA, Hagberg JM. Lactate threshold and distance running performance in young and older endurance athletes. *J Appl Physiol*. 1985;58:1281–1284. PubMed ID: 3988681 doi:10.1152/jappl.1985.58.4.1281
9. Conley DL, Krahenbuhl GS. Running economy and distance running performance of highly trained athletes. *Med Sci Sports Exerc*. 1980;12:357–360. PubMed ID: 7453514 doi:10.1249/00005768-198025000-00010
10. Stoggl TL, Sperlich B. Polarised training has greater impact on key endurance variables than threshold, high intensity, or high volume training. *Front Physiol*. 2014;5:33. PubMed ID: 24550842 doi:10.3389/fphys.2014.00033
11. Seiler S. What is best practice for training intensity and duration distribution in endurance athletes? *Int J Sports Physiol Perform*. 2010;5:276–291. PubMed ID: 20861519 doi:10.1123/ijspp.5.3.276
12. Tjelta LI. The training of international level distance runners. *Int J Sports Sci Coach*. 2016;11:122–134. doi:10.1177/1747954115624813
13. Arcelli E, Canova R. *Scientific training for the Marathon*. Monte Carlo, Monaco: International Association of Athletics Federation; 1999.
14. Oxford Centre for Evidence-based Medicine. *Levels of evidence*. Oxford, UK: University of Oxford; 2009:4–5.
15. de Morton NA. The PEDro scale is a valid measure of the methodological quality of clinical trials: a demographic study. *Aust J Physiother*. 2009;55:129–133. PubMed ID: 19463084 doi:10.1016/S0004-9514(09)70043-1
16. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Hillsdale, NJ: Lawrence Erlbaum Associates; 1988.
17. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41:3–13. PubMed ID: 19092709 doi:10.1249/MSS.0b013e31818cb278
18. Robinson DM, Robinson SM, Hume PA, Hopkins WG. Training intensity of elite male distance runners. *Med Sci Sports Exerc*. 1991;23:1078–1082. PubMed ID: 1943629 doi:10.1249/00005768-199109000-00013
19. Billat V, Demarle A, Slawinski J, Paiva M, Koralsztein JP. Physical and training characteristics of top-class marathon runners. *Med Sci Sports Exerc*. 2001;33:2089–2097. PubMed ID: 11740304 doi:10.1097/00005768-200112000-00018
20. Billat V, Lepretre PM, Heugas AM, Laurence MH, Salim D, Koralsztein JP. Training and bioenergetic characteristics in elite male and female Kenyan runners. *Med Sci Sports Exerc*. 2003;35:297–304. PubMed ID: 12569219 doi:10.1249/01.MSS.0000053556.59992.A9
21. Esteve-Lanao J, San Juan AF, Earnest CP, Foster C, Lucia A. How do endurance runners actually train? Relationship with competition performance. *Med Sci Sports Exerc*. 2005;37:496–504. PubMed ID: 15741850 doi:10.1249/01.MSS.0000155393.78744.86
22. Esteve-Lanao J, Foster C, Seiler S, Lucia A. Impact of training intensity distribution on performance in endurance athletes. *J Strength Cond Res*. 2007;21:943–949. PubMed ID: 17685689 doi:10.1519/R-19725.1
23. Tjelta LI, Enoksen E. Training characteristics of male junior cross country and track runners on European top level. *Int J Sports Sci Coach*. 2010;5:193–203. doi:10.1260/1747-9541.5.2.193
24. Stellingwerff T. Case study: nutrition and training periodization in three elite marathon runners. *Int J Sport Nutr Exerc Metab*. 2012; 22:392–400. PubMed ID: 23011657 doi:10.1123/ijsnem.22.5.392
25. Ingham S, Fudge BW, Pringle JS. Training distribution, physiological profile, and performance for a male international 1500m runner. *Int J Sports Physiol Perform* 2012;7:193–195. PubMed ID: 22634971 doi:10.1123/ijspp.7.2.193
26. Tjelta LI. A longitudinal case study of the training of the 2012 European 1500 m track champion. *Int J Appl Sports Sci*. 2013; 25:11–18. doi:10.24985/ijass.2013.25.1.11
27. Muñoz I, Seiler S, Larumbe E, Esteve J, Larumbe E, Esteve-Lanao J. Does polarized training improve performance in recreational runners? *Int J Sports Physiol Perform*. 2014;9:265–272. PubMed ID: 23752040 doi:10.1123/ijspp.2012-0350
28. Tjelta LI, Tonnessen E, Enoksen E. A case study of the training of nine times New York Marathon winner Grete Waitz. *Int J Sports Sci Coach*. 2014;9:139–158. doi:10.1260/1747-9541.9.1.139
29. Clemente-Suarez VJ, Gonzalez-Rave JM. Four weeks of training with different aerobic workload distributions-effect on aerobic performance. *Eur J Sports Sci*. 2014;14:S1–S7. doi:10.1080/17461391.2011.635708
30. Manzi V, Bovanzi A, Castagna C, Sinibaldi Salimei P, Volterrani M, Iellamo F. Training-load distribution in endurance runners: objective

versus subjective assessment. *Int J Sports Physiol Perform*. 2015;10: 1023–1028. PubMed ID: 25803237 doi:10.1123/ijspp.2014-0557

31. Clemente-Suarez VJ, Dalamitros AA, Nikolaidis PT. The effect of a short-term training period on physiological parameters and running performance: intensity distribution versus constant-intensity exercise. *J Sports Med Phys Fitness*. 2016;58:1–7. PubMed ID: 27813393 doi:10.23736/S0022-4707.16.06756-6
32. Mujika I. Quantification of training and competition loads in endurance sports: methods and applications. *Int J Sports Physiol Perform*. 2017;12:S29–S217. PubMed ID: 27918666 doi:10.1123/ijspp.2016-0403
33. Weyand P, Cureton K, Conely D, Sloniger M. Percentage anaerobic energy utilized during track running events. *Med Sci Sports Exerc*. 1993;25:S105. doi:10.1249/00005768-199305001-00588
34. Fiskerstrand A, Seiler S. Training and performance characteristics among Norwegian international rowers 1970–2001. *Scand J Med Sci Sports*. 2004;14:303–310. PubMed ID: 15387804 doi:10.1046/j.1600-0838.2003.370.x
35. Foster C, Rodriguez-Marroyo JA, de Koning JJ. Monitoring training loads: the past, the present, and the future. *Int J Sports Physiol Perform*. 2017;12:S22–S28. PubMed ID: 28253038 doi: 10.1123/ijspp.2016-0388

Study 2

<u>Kenneally M</u>, Casado A, Gomez-Ezeiza J, Santos-Concejero J. Training Intensity Distribution analysis by race pace *vs*. physiological approach in world-class middle- and long-distance runners. *Eur J Sport Sci* 21(6):819-26. 2020

Quality indicators: ISI-JCR Impact factor: 4.050. 21/88 (Q1) SPORT SCIENCES 2020

European Journal of Sport Science, 2021
Vol. 21, No. 6, 819–826, https://doi.org/10.1080/17461391.2020.1773934

ORIGINAL ARTICLE

Training intensity distribution analysis by race pace vs. physiological approach in world-class middle- and long-distance runners

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Abstract
This study aimed to analyse the training intensity distribution (TID) of a group of 7 world-class middle- and long-distance runners over 50 weeks using two different approaches to organise TID zones: (1) based on individual specific race pace and; (2) based on physiological parameters. Analysed training data included training volume, intensity and frequency. The average weekly volume for the group was 135.4 ± 29.4 km·week^{-1}. Training volumes for Z1, Z2 and Z3 were 88.5 ± 1.1%, 7.4 ± 0.8% and 4.1 ± 0.7% respectively for race-pace based approach, and 87.2 ± 1.2%, 6.1 ± 0.7% and 6.6 ± 0.9% respectively for the physiological approach. Differences were found between the approaches in Z2 (large effect, ES = 1.20) and Z3 (moderate effect, ES = 0.93). The approach based on race-pace zones produced pyramidal distributions in both middle- and long-distance runners across all phases of the season. The physiological approach produced polarised and pyramidal distributions depending of the phase of the season in the middle-distance runners, and pyramidal type TID across all phases of the season in the long-distance runners. The results of this study demonstrate that the training analysis in a world-class group of runners shows different TID when assessed relative to race pace *versus* to physiological zones. This highlights a potential deficiency in training analysis and prescription methods which do not make reference to specific performance. An approach which makes reference to both physiological and performance measures may allow for a more consistent and logical analysis.

Keywords: *Endurance, polarised training, threshold training, pyramidal training, running performance*

Highlights
- Training Intensity Distribution differs when analysed using 2 different methods-by race-pace and by physiological methods in world-class distance runners.
- The different methods of analysing training intensity distribution are flawed in their sensitivity to detecting changes in different zones: race-pace in Z2 and physiological in Z3.
- Considering race performance and physiological factors may provide a more complete analysis.

Introduction

Optimal training intensity distribution (TID) in endurance running remains a much debated topic in the scientific literature (Casado, Hanley, Santos-Concejero, & Ruiz-Perez, 2019 Esteve-Lanao, Foster, Seiler, & Lucia, 2007; Seiler & Kjerland, 2006;; Seiler SaT, 2009). The description of training intensity zones, which range from 3 to 7 zones, has classically been done using only the well-established metabolic factors related to running performance (Clemente-Suarez, Dalamitros, & Nikolaidis, 2018; Munoz et al., 2014 Stoggl & Sperlich, 2014;). These factors include running economy (Barnes & Kilding, 2015), VO_2max, vVO_2max (Stoggl & Sperlich, 2014) and lactate/ventilatory thresholds (Seiler & Kjerland, 2006). Most commonly three training zones are used: Zone 1 (Z1) relating to training performed below the first ventilatory or lactate thresholds; zone 2 (Z2) relating to training performed between the ventilatory or lactate thresholds;

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and zone 3 (Z3) relating to training performed above the second ventilatory or lactate threshold. The description of training intensity distribution has broadly fallen into three categories (Kenneally, Casado, & Santos-Concejero, 2018): (1) pyramidal or traditional; whereby there is a sequentially decreasing volume of training performed in higher training intensity zones; (2) threshold training, whereby a relatively larger proportion of training is performed in Z2, with Z3 again being the smallest in terms of volume; (3) polarised training, whereby there is a reduction of training performed in Z2, and a corresponding increase in training performed in Z3.

A meta-analysis by Rosenblat, Perrotta, and Vicenzino (2018) focussed on comparing the effect of polarised vs. threshold training on endurance sport performance. They concluded that polarised training produced significantly greater improvements in time trial performance and suggested that coaches should consider using polarised training to optimise endurance training and performance. However, this suggestion contrasts with the training practices of some elite level endurance runners (Kenneally et al., 2018). Recent work by Casado, Hanley, and Ruiz-Pérez (2019) and Tjelta (2019) showed that the training of elite distance runners is actually characterised by large volumes in the *threshold* zone. Traditionally this pace would be considered to fall into Z2 physiologically. It should, however, be noted that in these studies, the authors did not specifically consider physiological zones when analysing the training data, as they sought to examine whether "deliberate practice" characterised training of elite runners, and as such, physiological zones were not needed as a reference.

Bellinger, Arnold, and Minahan (2019) added further to this potential conflict, in a study in which they compared 3 different methods of analysis of TID; by running pace, heart rate and rating of perceived exertion (RPE). 3 zones were used in this study, and the times spent in Z2 and Z3 significantly differed depending on the method of analysis used. In this instance, running speed based analysis suggested that a polarised distribution was being employed, whereas heart rate based analysis suggested a pyramidal distribution of the same training. Kenneally et al. (2018) also recently proposed a novel way to create training intensity zones based on percentages of the athletes' event-specific target race pace. Recent work (Esteve-Lanao et al., 2007; Casado, Hanley, Santos-Concejero, et al., 2019; Stoggl & Sperlich, 2014; Clemente-Suarez et al., 2018) which has focussed on the effectiveness of endurance training both in intensity distribution and periodisation has examined either change in physiological/metabolic parameters or time trial performance as a main outcome rather than actual competition or race performance. Thus, the contention is that this difference may lead to differing interpretations of how to optimise training.

It is against this background that this study aims to analyse the training of a group of world-class athletes over a 12-month period, using an approach in which their training is organised into zones based on individual event specific race pace/performance, and to describe how such training is periodised over the course of the season. This is presented against the same training organised into the traditional physiological zones, based on testing done at the start of their season. We feel that proof of improvement of physiological parameters or time trial performance within a defined timeframe, when assessed independent of each other and of concurrent race performance, is not consistent with preparing for endurance running at an elite level, where race performance is the primary targeted outcome, and where longitudinal development and improvement is sought.

Methods

Participants

Seven elite runners (3 men and 4 women) participated in this study. During the analysed period, all participants but one achieved top-8 in the previous major athletics championships. The athletes are coached by the same coach and are part of the same training group, which has been consistently producing athletes who qualify for major athletics events (Commonwealth Games, World Championships and Olympic Games). The coach has more than 15 years of experience training multiple international medallist athletes. The athletes were sub-grouped into middle-distance runners (800-1500 m athletes) and long-distance runners (5000 m–10,000 m athletes). All participants provided written informed consent. The Ethics Committee for Research on Human subjects of the University of the Basque Country UPV/EHU (CEISH-UPV/EHU 94/2017) approved this study, which was conducted in compliance with the principles of the Declaration of Helsinki.

Data collection and analysis

A detailed daily log of training data prescribed by the coach and updated by the athletes was provided. Data were collected over a 50 week training period. The season was divided into two preparation cycles, one of 28 weeks for the World Athletics Championships (April 2017 to August 2017), followed by 20 weeks until the Commonwealth Games (April 2018), with two weeks of active rest in between. Additionally, anthropometric and physiological data were collected following each preparation phase. A maximal incremental treadmill test was conducted to determine the physiological profile of the athlete. The protocol consisted of increments of 1 km·h^{-1} every 5 min, starting at 14 km·h^{-1} for women and 15 km·h^{-1} for men, respectively, until volitional exhaustion. During the test, oxygen uptake (VO_2) was continuously measured using a gas analyser system (Oxycon Pro, Eric Jaeger, Hoechberg, Germany). VO_{2max} was defined as the maximum 30 s VO_2 value recorded and vVO_{2max} was defined as the minimum speed at which this volume was reached. Blood samples were collected from the earlobe during the last 30 s of each increment to analyse lactate concentration (The Edge^{TM} Lactate Analyser). Lactate thresholds were calculated using the D_{max} method (Cheng et al., 1992).

Analysed training data included training volume, intensity and frequency, as well as session intention. Then, TID was organised and compared based on race-pace (Kenneally et al., 2018) (Z1: <80% race pace; Z2: 80–95% race pace; Z3 > 95% race pace) and physiological zones (Seiler SaT, 2009; Stoggl & Sperlich, 2015) (Z1: <LT1; Z2: LT1 to LT2; Z3 >LT2).

Training philosophy of the group

The coach of the group observed employs an outcome based process to his coaching. It is focussed primarily on the achievement of race performance, as defined by time achieved in a specific event, or by championship performance. Therefore the 2 main outcomes which training for this group is targeted toward are:

1. Time achieved over a specific distance i.e. mean race pace over a specific distance
2. Ability to finish a race in a championship at a specific pace, defined externally, based on either what is required to make a final or win a medal, depending on the athlete. The coach defined these as pace over last 400 m for 800 m/1500 m, and over the last 1000 m for 5000/10,000 m

The coach prescribed sessions for the athletes using a combination of heart rate and specific pace. Heart rate was used in the prescription of "threshold" focussed sessions, and was used to ensure that the athletes maintained their heart rate at a level consistent with Z2, as measured in the treadmill testing. Pace based sessions were prescribed relative to specific race paces, informed by the coaches experience. The athletes did perform some short hill sessions at certain phases of the year. These sessions were interval sessions with interval duration of no more than 800 m. For these sessions the athletes were instructed to run at 5k effort. For the purposes of analysis these sessions were included in Z3 for both physiological and race-pace based approach.

Statistical analysis

All values are expressed using a mean ± standard deviation (SD). The volume of training in race pace based zones was compared to each other and to physiological based zones using Cohen *d* (Hopkins, Marshall, Batterham, & Hanin, 2009). The magnitude of differences, or effect size (ES) of this comparison was interpreted as small (>0.2 and <0.6), moderate (≥0.6 and <1.2), large (≥1.2 and <2) and very large (≥2.0) according to the scale proposed by Hopkins et al. (Hopkins et al., 2009).

Results

Participants characteristics

The descriptive characteristics, physiological variables and performance of the participants are presented in Table I. The male middle-distance athletes achieved times (min:s) ranging 1:45.60–1:46.77 (800 m) and 3:34.38–3:36.30 (1500 m). The female middle-distance athletes achieved times ranging 2:00.24–2:04.89 (800 m) and 4:04.93–4:10.42 (1500 m). The male long-distance athletes achieved times ranging from 13:05.23–13:26.38 (5000 m). The female long-distance athletes achieved times ranging from 15:06.67–15:18.91 (5000 m).

Training volume and intensity distribution

The mean weekly volume for the group was 135.4 ± 29.4 km·week^{-1}. Specifically, the long-distance athletes performed an averaged of 145.9 ± 27.9 km·week^{-1}, whereas the middle-distance runners performed 127.4 ± 28.7 km·week^{-1}. A sample week from General Preparation Phase 1 is shown in Table II. The General Preparation Phase took place between October 2017 and January 2018, following a 2 week recovery phase.

Comparison of training zones

Figure 1(C and F) displays the comparison of zones via race-pace vs. physiological methods for the

Table I. Performance and physiological characteristics of participants (Mean ±SD)

	Male (n = 4)	Female (n = 3)
Age (yrs)	24.7 ± 2.5	27.5 ± 0.7
BW (kg)	66.2 ± 4.3	51.4 ± 3.3
VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	73.8 ± 2.1	61.4 ± 4.2
vVO_{2max} ($km \cdot h^{-1}$)	22.1 ± 0.4	19.3 ± 1.1
LT1 ($km \cdot h^{-1}$)	17.9 ± 0.8	16.1 ± 0.1
LT2 ($km \cdot h^{-1}$)	19.7 ± 0.6	17.5 ± 0.07
RE ($mL \cdot kg^{-1} \cdot km^{-1}$)	191.9 ± 6.2	173.1 ± 17.1
Performance	1:45.60–1:46.77 (800 m)	2:00.24–2:04.89 (800 m)
	3:34.38–3:36.30 (1500 m)	4:04.93–4:10.42 (1500 m)
	13:05.23–13:26.38 (5000 m)	15:06.67–15:19.81 (5000 m)

Note: BW, body weight; VO_{2max}, maximal oxygen uptake; vVO_{2max}, velocity at which maximal oxygen uptake is reached; LT1, speed corresponding to the first lactate threshold; LT2, speed corresponding to the second lactate threshold; RE, running economy.

middle- and long-distance groups respectively. The middle distance group (Figure 1(C)) showed no differences for Z1 by the two methods of analysis. There were moderate effect sizes for the differences between the two methods used to calculate Z2 (ES = 0.63) and Z3 (ES = 0.61), with Z2 greater by race-pace based analysis and Z3 greater by physiological analysed. The long-distance group (Figure 1 (F)), showed no differences between the two methods of analysis for any zone.

As a group there was no difference between Z1 when calculated as race-pace based zones or using physiologically based zones. However, there was a large effect size (ES = 1.20) for the difference between the two methods used to calculate Z2, and a moderate effect for the Z3 difference (ES = 0.93).

TID across the season

Figure 1 also shows the training intensity distribution for the subgroups across the microcycles of the season. The approach based on race-pace zones produced pyramidal distributions for both groups across all phases of the season (Figure 1(A and D)). The physiological approach produced a more polarised type distribution in the middle-distance runners (i.e. more training performed in Z3 than Z2), with the General Prep phase the exception-showing a pyramidal distribution (Figure 1(B and E)). The long-distance subgroup was a more pyramidal type distribution on analysis using physiological zones across all phases of the season (Figure 1(E)). Significant differences in zones between approaches are noted only in the "Specific Prep 1" and "Competitive 2" phases in the middle-distance subgroup in Z2 (Figure 1(A)). The analysis by race pace returned higher values for this zone in these phases, effect sizes 0.93 (moderate) and 1.2 (large), respectively.

Race-pace and physiological method comparison

Figure 2 shows how the race-pace approach and the physiological approach interact when mean running volume (at a given velocity) is plotted against absolute running speed. The percentage volume is represented on a log scale, because the relative volume of training done at lower speeds is so much greater than at higher speeds. In the figure 16 km h^{-1} represents volume of training done up to velocities of 16 km h^{-1}. All other points represent the volume performed between the previous point and the relevant one (e.g. 17 km h^{-1} represents training volume performed between 16 and 17 km h^{-1}).

It shows the middle distance group (Figure 2(A)) with a narrower physiological Z2 velocity band than

Table II. Sample week from general preparation phase 1

	AM	PM
Monday	60 min easy running	30 min easy running + drills and 150 m strides
Tuesday	8 × 1 km (60 s recovery). Run at current 10 km race pace, with 5th and 7th reps run 10 s faster	30 min easy running
Wednesday	60 min easy running	30 min easy running
Thursday	9 km "Threshold" run-determined by Heart Rate	30 min easy running
Friday	60 min easy running	
Saturday	6 × 800 m Hills-pace subjective-5k "effort"	30 min easy running
Sunday	105 min easy running	

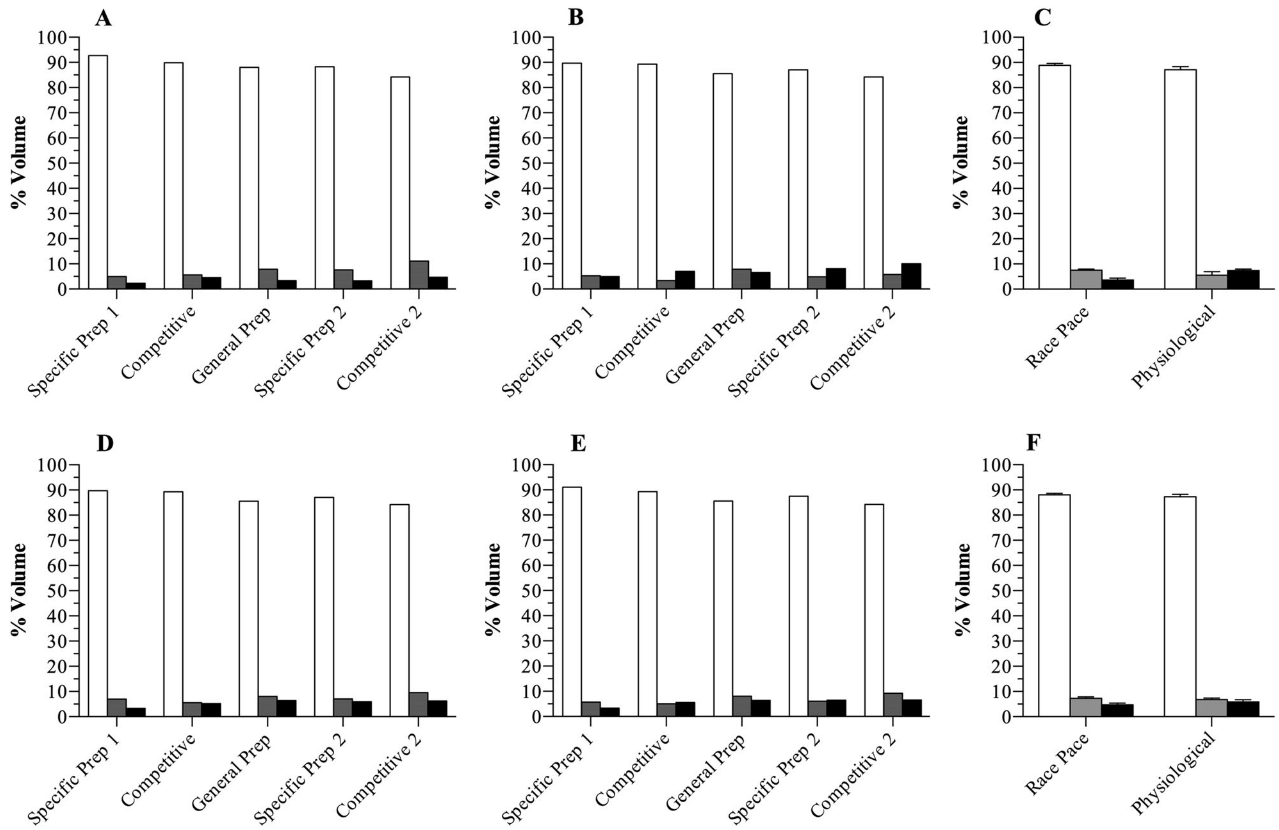

Figure 1. Training intensity distribution (TID) comparison. TID using a race-pace based approach in the middle-distance runners during the different phases of the athletic season (A), TID using a physiological approach in the middle-distance runners during the different phases of the season (B), TID comparison between a physiological and a race-pace based approach in the 800/1500 runners over 50 weeks (C). TID using a race-pace based approach in the long-distance runners during the different phases of the season (D), TID using a physiological approach in the long-distance runners during the different phases of the season (E), TID comparison between a physiological and a race-pace based approach in the 5000/10,000 m runners over 50 weeks.

the long-distance group (Figure 2(B)), and shows at what points target race speeds are.

Discussion

The main finding of this study was that the training intensity distribution of a group of world-class distance runners performed was more consistently linked to proportions of race-pace than physiological parameters. Given that the expressed main coaching intention for the group was the development of race pace, this is not a surprising finding. Figure 2 provides clarity to this point. The arbitrary percentages of race pace chosen for analysis have resulted in Z2 by race-pace approach spanning a much wider range than Z2 by physiological approach (~4 km h^{-1} vs. 2 km h^{-1}), and therefore is less sensitive to changes in intensity distribution around these paces. Equally the opposite is true when Z3 is considered by physiological approach vs. race-pace based approach.

When viewed over the course of the different phases of a season, race-pace based analysis returned a consistent pyramidal TID. However, the TID was more variable – between pyramidal and polarised – when analysed via physiological parameters. Interestingly, the athletes performed a relatively high proportion of their training in Z2, consistent with recent studies (Bellinger et al., 2019; Casado, Hanley, Santos-Concejero, et al., 2019). This was true regardless of whether training was analysed physiologically or by race pace, although as noted above Z2 by race-pace approach included intensities well in excess of physiological “threshold”. Nonetheless the current authors have also noted this use of training at threshold intensity in world-class distance runners, and feel that the race-pace based analysis at least links training analysis to coaching intention in a number of other elite training groups (Kenneally et al., 2018).

The volume of training done by the group in the current analysis is relatively consistent with what has been reported in recent literature on world class

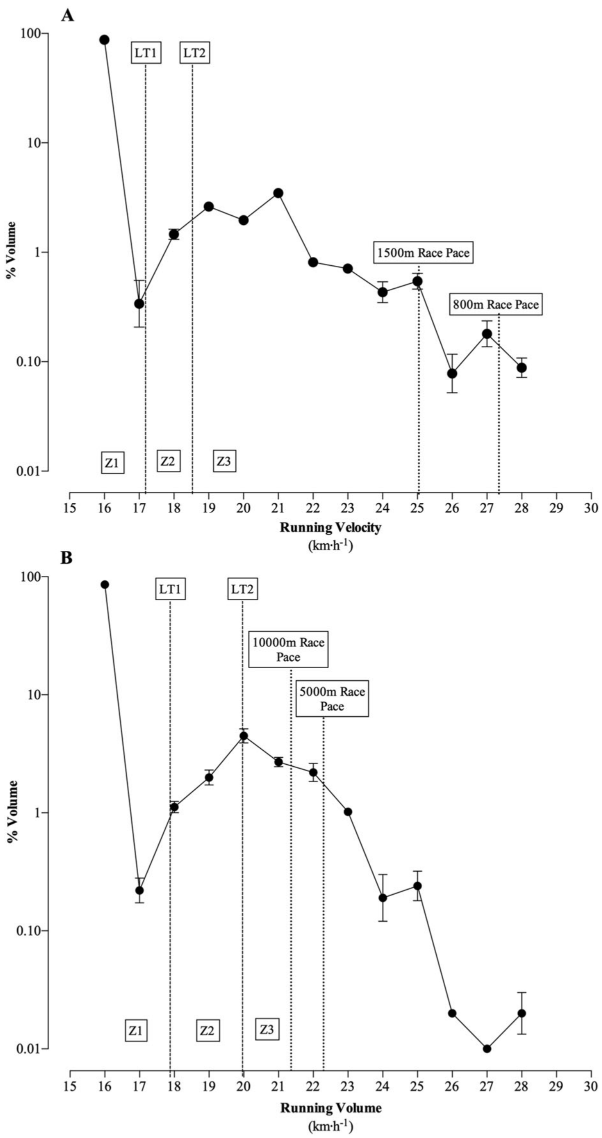

Figure 2. Training volume (%) plotted against absolute speed over the 50 analysed weeks with physiological zone delineation and race-pace points included; in the 800/1500 m runners (A), in the 5000 m/10,000 m runners (B).

distance runners (Tjelta, 2016; Tjelta, 2019). The slightly lower volumes seen may be explained by the fact that non-regular training weeks were not excluded from the total volume. The athletes showed peak weeks in excess of 160 km, which is entirely consistent with what has previously been reported in the studies aforementioned. Interestingly, close to 85–90% of this groups' total volume lies in Z1, regardless of method of analysis, which is higher than the traditionally proposed "80:20" rule (Seiler & Kjerland, 2006). This states that approximately 20% of total volume will be performed in higher intensity zones, with the remainder low intensity. The current findings, however, are consistent with Casado, Hanley, Santos-Concejero's (2019) finding that volume of easy running was the best predictor of race performance.

Z2 (*threshold* zone) has traditionally been the zone around which much of the debate has centred. Recent work has suggested that training in this zone is less effective than pyramidal or polarised training (Ingham, Fudge, & Pringle, 2012; Rosenblat et al., 2018; Stellingwerf, 2012; Stoggl & Sperlich, 2015). The results of this study demonstrate than an elite group of distance runners, who were successful during the time period study, used "threshold training". By physiological approach analysis the middle-distance runners in this group performed slightly more training in Z3 than Z2-although the difference was minimal. The long-distance athletes demonstrate a pyramidal approach (Figure 1(B and E)). This is despite the training being performed being virtually identical. The reason for this apparent contradiction lies in coaching intention and the differences between velocities at lactate threshold in the 2 subgroups of athletes. The longer distance athletes tended to have higher velocities at lactate threshold, therefore training that lay just below the threshold in that group would lie just above the threshold in the middle-distance group i.e. Z3. However training sessions at this intensity were often performed as a whole group-thereby creating the difference.

The analysis showed that when the training of this group of elite distance runners is considered relative to their individual target race-pace, a pyramidal type training intensity distribution is seen, regardless of phase of training (Figure 1(C and F)). This pyramidal distribution was also preserved across athletes competing at different race distances, ranging from 800 m to 10,000 m. However, the absolute training intensities of this group were similar for athletes competing over different distances, and as a result, differences were seen in the volumes in respective relative zones. Longer distance athletes (5000/10,000 m) had more volume in their higher relative intensity zones than middle-distance athletes, although both demonstrated pyramidal distributions.

Conversely, analysis by physiological zones demonstrated a polarised type distribution in the middle-distance runners across 4 of the 5 phases of the season (Figure 1(B)), while the pyramidal nature of the long-distance athletes TID was preserved (Figure 1(E)). This reflects the fact that the longer distance athletes had higher velocities at lactate threshold than their shorter counterparts, so that their pace/speed threshold for "higher intensity" work occurred at greater speeds.

This dichotomy has been alluded to previously by Kenneally et al. (2018) and is highlighted very well in this study, as both groups performed virtually the same training-with the only variation arising in volume of easy/Z1 running. The more recent paradigm is to recommend polarised type training based on physiological parameters, whereby physiological testing, zone creation and training prescription feeds forward to race performance, which does not take into account the variety of inputs outside the traditional metabolic considerations, which can affect endurance performance. Further to this, the our contention is that a move away from "threshold" training, based on the recent studies above described, would be mistaken in its conception. This is because world class runners perform large proportions of their training in Z2 (Casado, Hanley, & Ruiz-Pérez, 2019; Casado, Hanley, Santos-Concejero, et al., 2019; Tjelta, 2019), and because the physiological approach links performance to physiological parameters only, despite a failure in the literature to provide practical examples of where physiological characteristics can predict running performance. However, analysis by race-pace based approach alone is also imperfect using our current delineations, because Z2 spans a range of intensities which will provide very different training stimuli.

An alternative paradigm, which can incorporate metabolic, cardiopulmonary, neuromuscular and biomechanical factors is proposed. In this paradigm, race performance informs training prescription, as well as interpretation of physiological testing. We suggest the potential for allometric profiling of physiological parameters based on contemporaneous race performance, to attempt to create a "signature" physiological profile which corresponds with specific race performance. Such an approach recognises the multifactorial nature of the physiological components of distance running performance, and the potential "substitution effect" of individual parameters. This can also allow for non-physical factors such as psychology/motivation. This approach may mirror the approach of Sandford et al. (Julio et al., 2020; Sandford, Allen, Kilding, Ross, & Laursen, 2019) in their concept of an Anaerobic Speed Reserve (ASR), in that they attempt to link external demands of race performance and physiological factors influencing middle-distance running. In this model, strictly limited to middle-distance (800/1500 m) running performance, training is expressed relative to ASR, which is the difference between vVO_{2max} and maximal sprint speed.

The impact of the fact that this is a study involving elite athletes should also be considered. In elite runners, the difference between maximal sprint speed, vVO_2 max, vLT and low intensity running will naturally be far greater than in recreational or untrained individuals, given that elite is being defined by how fast they can run. Therefore zone delineation is much more clear. In untrained and recreational runners, it is conceivable and probable that Z2, for example, represents such a narrow pace band that the difference in subjective intensity between it and Z3 is difficult to distinguish, potentially allowing for training mistakes. This may also highlight a potential weakness of using a polarised approach, as it will reduce the amount of specific training done for distances in duration of 40–60 min. Interestingly, however, a recently published paper compared the effects of polarised and threshold training (described as focussed endurance training) in 38 recreational runners over 8 weeks, and demonstrated similar improvements regardless of TID employed.

Conclusions

The results of this study demonstrate that analysis of training in an elite group of middle- and long-distance runners returned volumes of running regularly in excess of 150 $km \cdot wk^{-1}$. All the athletes in the group performed significant portions of their training at threshold intensity, regardless of event distance. The middle-distance runners in this group performed more training in Z3 than long-distance runners across the season when assessed using a physiological approach. However this difference reduced when training was analysed relative to race-pace. Both physiological and race-pace based approaches were demonstrated to be flawed in their sensitivity to detect changes in intensity distribution; race-pace based approach for Z2 and physiological approach for Z3. Thus our results highlight a potential deficiency in any training analysis and prescription method which does not make reference to specific performance as well as physiological metrics. An approach which makes reference to both physiological and performance measures may allow for a more consistent and logical analysis.

Practical applications

We suggest that the results of this study support an approach to training planning and prescription whereby physiological data is collected systematically, and then the metrics are systematically compared to race performance. This may provide a method of coaching which allows for the appropriate development of physiological characteristics, while still allowing for feedback from, and feed-forward to, race performance. The relative importance of physiological characteristics may then be individualised once a bank of race performances have been collected and compared with physiological data. Other less well defined factors such as psychological, biomechanical can therefore be accounted for by such an approach. In this way the practical use of physiological testing may become more evident to coaches currently less experienced in its use and interpretation.

Acknowledgements

We gratefully thank the athletes and coach (Nic Bideau) participating in this study for their generosity in supporting the research efforts employed to conduct it.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

Barnes, K. R., & Kilding, A. E. (2015). Running economy: Measurement, norms, and determining factors. *Sports Medicine – Open*, *1*(1), 1–8.

Bellinger, P., Arnold, B., & Minahan, C. (2019). Quantifying the training-intensity distribution in runners: the influence of different methods of training quantification. *International Journal of Sports Physiology and Performance*, 1–5. Epub ahead of print. doi:10.1123/ijspp.2019-0298.

Casado, A., Hanley, B., & Ruiz-Pérez, L. M. (2019). Deliberate practice in training differentiates the best Kenyan and Spanish long-distance runners. *European Journal of Sport Science*. Epub ahead of print. doi:10.1080/17461391.2019.1694077

Casado, A., Hanley, B., Santos-Concejero, J., & Ruiz-Perez, L. M. (2019). World-class long-distance running performances are best predicted by volume of easy runs and deliberate practice of short-interval and tempo runs. *Journal of Strength and Conditioning Research*. Epub ahead of print. doi:10.1519/JSC.0000000000003176

Cheng, B., Kuipers, H., Snyder, A. C., Keizer, H. A., Jeukendrup, A., & Hesselink, M. (1992). A new approach for the determination of ventilatory and lactate thresholds. *International Journal of Sports Medicine*, *13*(7), 518–522.

Clemente-Suarez, V. J., Dalamitros, A. A., & Nikolaidis, P. T. (2018). The effect of a short-term training period on physiological parameters and running performance: Intensity distribution versus constant-intensity exercise. *Journal of Sports Medicine and Physical Fitness*, *58*(1-2), 1–7.

Esteve-Lanao, J., Foster, C., Seiler, S., & Lucia, A. (2007). Impact of training intensity distribution on performance in endurance athletes. *Journal of Strength and Conditioning Research*, *21*(3), 943–949.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise*, *41*(1), 3–13.

Ingham, S. A., Fudge, B. W., & Pringle, J. S. (2012). Training distribution, physiological profile, and performance for a male international 1500-m runner. *International Journal of Sports Physiology and Performance*, *7*(2), 193–195.

Julio, U. F., Panissa, V. L. G., Paludo, A. C., Alves, E. D., Campos, F. A. D., & Franchini, E. (2020). Use of the anaerobic speed reserve to normalize the prescription of high-intensity interval exercise intensity. *European Journal of Sport Science*, *20*(2), 166–173.

Kenneally, M., Casado, A., & Santos-Concejero, J. (2018). The effect of periodization and training intensity distribution on middle- and long-distance running performance: A systematic review. *International Journal of Sports Physiology and Performance*, *13*(9), 1114–1121.

Munoz, I., Seiler, S., Bautista, J., Espana, J., Larumbe, E., & Esteve-Lanao, J. (2014). Does polarized training improve performance in recreational runners? *International Journal of Sports Physiology and Performance*, *9*(2), 265–272.

Rosenblat, M. A., Perrotta, A. S., & Vicenzino, B. (2018). Polarized vs. threshold training intensity distribution on endurance sport performance: A systematic review and meta-analysis of randomized controlled trials. *Journal of Strength and Conditioning Research*, *33*(12), 3491–3500.

Sandford, G. N., Allen, S. V., Kilding, A. E., Ross, A., & Laursen, P. B. (2019). Anaerobic speed reserve: A key component of elite male 800-m running. *International Journal of Sports Physiology and Performance*, *14*(4), 501–508.

Seiler, K. S., & Kjerland, G. O. (2006). Quantifying training intensity distribution in elite endurance athletes: Is there evidence for an "optimal" distribution? *Scandinavian Journal of Medicine and Science in Sports*, *16*(1), 49–56.

Seiler SaT, E. (2009). Intervals, threshold and long slow distance: The role of intensity and duration in endurance training. *Sports Science*, *13*, 32–53.

Stellingwerf, T. (2012). Case study: Nutrition and training periodization in three elite marathon runners. *International Journal of Sport Nutrition and Exercise Metabolism*, *22*(5), 392–400.

Stoggl, T., & Sperlich, B. (2014). Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. *Frontiers in Physiology*, *5*, 1–9.

Stoggl, T. L., & Sperlich, B. (2015). The training intensity distribution among well-trained and elite endurance athletes. *Frontiers in Physiology*, *6*, 1–14.

Tjelta, L. I. (2016). The training of international level distance runners. *International Journal of Sports Science & Coaching*, *11*(1), 122–134.

Tjelta, L. I. (2019). Three Norwegian brothers all European 1500 m champions: What is the secret? *International Journal of Sports Science & Coaching*, *14*(5), 694–700.

Study 3

Kenneally M, Casado A, Gomez-Ezeiza J, Santos-Concejero J. Training characteristics of a World Championship 5000-m Finallist and Multiple Continental Record Holder over the year leading to a World Championship final. *Int J Sports Physiol Perform* 17 (1):142-6. 2022

Quality indicators: ISI-JCR Impact factor: 4.050. 22/88 (Q1) SPORT SCIENCES 2020

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2021-0114

Human Kinetics
BRIEF REPORT

Training Characteristics of a World Championship 5000-m Finalist and Multiple Continental Record Holder Over the Year Leading to a World Championship Final

Mark Kenneally, Arturo Casado, Josu Gomez-Ezeiza, and Jordan Santos-Concejero

Purpose: Optimal training for endurance performance remains a debated topic. In this case study, the training of a world-class middle-/long-distance runner over a year's duration is presented. ***Methods:*** The training is analyzed via 2 methods to define training intensity distribution (TID) (1) by physiological zones and (2) by zones based on race pace. TID was analyzed over the full season, but also over the final 6, 12, and 26 weeks to allow for consideration of periodization/phases of season. The results of both methods are compared. Other training data measured include volume and number of sessions. ***Results:*** The average weekly volume for the athlete was 145.8 (24.8) km·wk^{-1}. TID by physiological analysis was polarized for the last 6 weeks of the season but was pyramidal when analyzed over the final 12, 26, and 52 weeks of the season. TID by race-pace analysis was pyramidal across all time points. The athlete finished 12th in the final of the World Championship 5000-m and made the semifinal of the 1500-m. He was ranked in the top 16 in the world for 1500, 5000, and 10,000 m. ***Conclusion:*** The results of this study demonstrate a potential flaw with recent work suggesting polarized training as the most effective means to improve endurance performance. Here, different analysis methods produced 2 different types of TID. A polarized distribution was only seen when analyzed by physiological approach, and only during the last 6 weeks of a 52-week season. Longer-term prospective studies relating performance and physiological changes are suggested.

Keywords: endurance, training intensity distribution, polarized training, pyramidal training, running performance

Optimal training for endurance performance has been studied extensively over recent years.[1,2] Much of the work has focused on the specific effect of training on physiological characteristics over short time frames and has suggested that real-life performance can be developed from these effects.[3] Three main types of training intensity distributions (TID) have been proposed[4] pyramidal, polarized, and threshold, which are characterized by the proportion of training done in different intensity zones.[4,5] Polarized training has been proposed as the best way to improve the physiological characteristics classically associated with distance-running performance, that is, maximal oxygen consumption (VO_2max), velocity at lactate threshold (vLT), and running economy.[6] However, detail around what an "optimal" physiological profile for different events should be has been missing. Thus, an approach to training planning where physiological data are collected, and then, compared with race performance may provide a method which allows for the appropriate development of physiological characteristics, while allowing feedback from, and feed-forward to, race performance.[7]

It is proposed that this "race-pace" (RP) -based approach is relatively common at elite level.[7] This case study presents 52 weeks of training of an athlete leading to the final of the World Championship 5000 m in Doha, Qatar, in October 2019. The aims were (1) to examine 52 weeks of training through a combination of TID quantification methods, such as physiological and race pace–based approaches, and (2) to identify possible relationships between physiological and training characteristics in this world-class runner.

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Methods

Subject

The case study athlete is a male middle-distance runner. Over the timeframe examined, the athlete was 23–24 years old. The athlete's height was 1.88 m and body weight was ~67 kg.

Training and Competition Data

The subject provided all training data for the period October 2018 to October 2019. Training data consisted of distance (in kilometers), duration (h:min), and session intention (easy/threshold/interval). Race schedule and results were also provided by the athlete.

The athlete performed physiological testing just before the 2-week break preceding the examined timeframe. Results are presented in Table 1. This was an incremental treadmill test, starting at 15 km·h^{-1}, and increasing by 1 km·h^{-1} every 5 minutes until volitional exhaustion. O_2 uptake was constantly measured using a gas analyzer system (Oxycon Pro; Carefusion Germany 234 GmbH, Hoechberg, Germany). Blood samples were collected from the earlobe during the last 30 seconds of each increment to analyze lactate concentration (The Edge Lactate Analyzer; Apexbio, Hsinchu City, Taiwan).

Calculation of Volumes in Each Intensity Zone

Sessions were analyzed, and running volume performed at different paces was allocated to speed "buckets" in 1 km·h^{-1} increments. The volume in each intensity zone, by both methods, was then calculated by adding the volume in the "buckets" relevant to each zone. When sessions were performed around the boundaries of intensity zones, manual analysis of the session was performed, and volume was allocated accordingly. The average pace of continuous sessions was used unless the athlete stated that a change of pace of greater than 1 km·h^{-1} occurred within the session. A similar process was used for the individual repetitions within interval sessions, with volume being distributed accordingly. The time period studied was subdivided into 4 periods to demonstrate change in training structure over the whole year. These 4 periods were 52 weeks, 26 weeks, 12 weeks, and 6 weeks.

Physiological Approach. Zone 1 (Z1), Zone 2 (Z2), and Zone 3 (Z3) were defined as: <vLT1(18.3 km·h^{-1}), between vLT1 and vLT2 (20.3 km·h^{-1}), and >vLT2, respectively. These values were obtained from the athlete's testing data provided.

Table 1 Physiological and Performance Characteristics of the Participant

Characteristic	
Height, m	1.88
Weight, kg	67
VO_2peak, mL·kg^{-1}·min^{-1}	73.5
Velocity at LT1, km·h^{-1}	18.3
Velocity at LT2, km·h^{-1}	20.3
Running economy at LT1, mL·kg^{-1}·km^{-1}	193
Running economy at LT2, mL·kg^{-1}·km^{-1}	198
1500-m PB (achieved during period)	3:31.81
3000-m SB/PB	7:38.22/7:34.79
5000-m SB/PB	13:05.63/13:05.23
10,000-m PB (achieved during period)	27:23.80

Abbreviations: LT1, first lactate threshold; LT2, second lactate threshold; PB, personal best; SB, season best.

Race-Pace Approach. Z1, Z2, and Z3 were defined as described previously[4] (RP was defined as 22.9 km·h^{-1}, the pace of the athlete's 5000 m personal best): Z1 <80% RP (18.3 km·h^{-1}), Z2 80% to 95% RP (18.3–21.8 km·h^{-1}), and Z3 >95% of RP.

Session Intention and Types

The coach prescribed sessions for the athlete using a combination of heart rate and specific pace:

Easy sessions were all nonspecific running sessions and were Z1 regardless of analysis type.

Threshold sessions were prescribed using heart rate to ensure that the athlete maintained his heart rate at a level consistent with physiological Z2, as measured in the treadmill testing.

Interval sessions were prescribed relative to specific race paces. These sessions included both Z2 and Z3 intensities by both methods of analysis. The athlete performed some short hill sessions at certain phases of the year. In these sessions, repetitions were not longer than 800 m, and the athlete was instructed to run at 5-km effort. For the purposes of analysis, these sessions were included in Z3 for both TID approaches.

Results

Performance

The athlete's seasons best performances are illustrated in Table 1. He raced 20 times and achieved personal bests-over 1500 and 10,000 m, the latter being a national record. In addition, the athlete qualified for and competed in the 1500 and 5000 m at the World Championship in Doha . He made the final of the 5000 m, finishing 12th and the semifinal of the 1500 m. He is currently ranked 14th over 1500 and 5000 m and 16th over 10,000 m, in the official World Athletics Rankings.

Training Summary

The athlete's' training over the year is displayed relative to running speeds and physiological zones in Figure 1. Training volume is displayed in km (SD) in Figure 2 for all time periods. Training

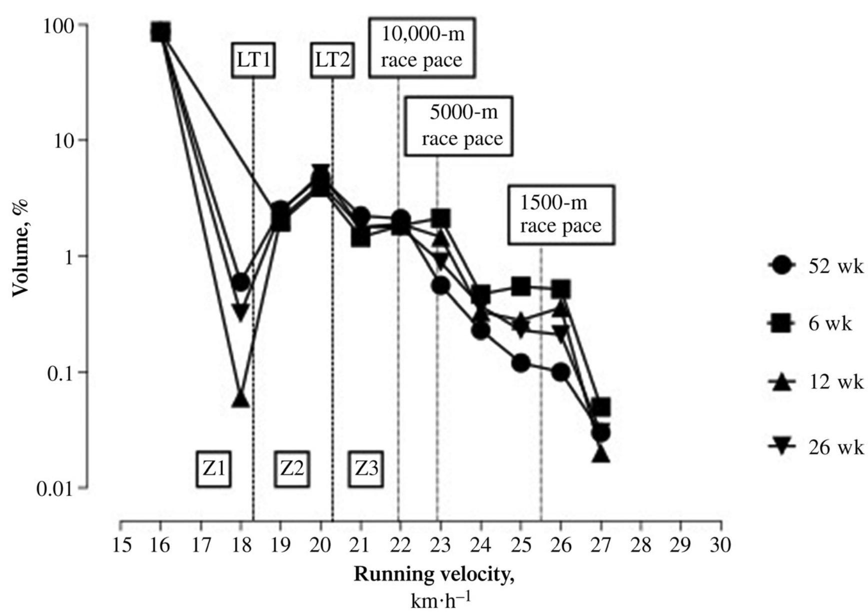

Figure 1 — Training volume plotted against absolute speed over the last 6, 12, 26, and 52 analyzed weeks with physiological zone delineation and race-pace points included. LT1 indicates first lactate threshold; LT2, second lactate threshold; Z, zone.

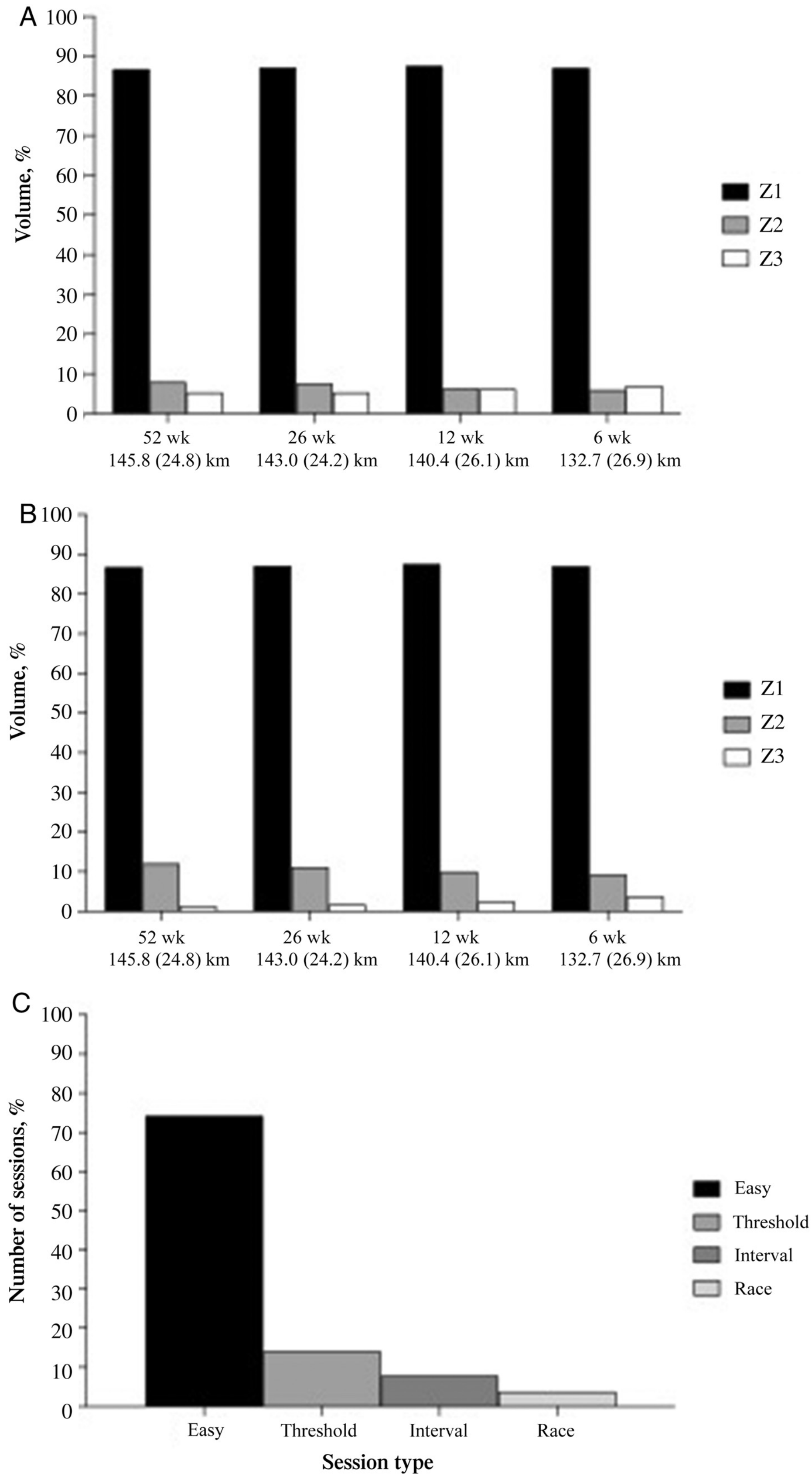

Figure 2 — The training intensity distribution by (A) physiological approach and (B) race-pace approach over different periods of the studied year and (C) session type by percentage over the year.

week examples for the early season and the competitive phase are provided in Table 2.

Training Volume Relative to Physiological and RP Zones

Figure 2A and 2B illustrate the volume and proportion of training done in each of the physiological and race-pace zones, respectively, across the year. A pyramidal structure is seen in the physiological analysis of the 52, 26, and 12 weeks prior to the World Championship. The last 6 weeks, however, demonstrate a slightly polarized distribution. A pyramidal distribution is seen via RP analysis across all time periods.

Training Session Types

The athlete performed 528 sessions over the course of the 52 weeks, including races. Figure 2C illustrates the proportion of session types performed.

Discussion

The case study presents the training of a world-class middle-distance runner over the course of a successful season. The running volume observed over the course of the season is in line with previous work detailing elite training volumes.[8] The large easy running volume is now a recurring feature across studies.[9,10] In this study, TID changes across the season, relative to RP and physiological approaches. RP demonstrates an increasing specificity of work done around race pace as goal competition approaches (Figure 2B). A switch from pyramidal to polarized distribution is seen in the last 6 weeks before goal competition, when physiological zones are considered (Figure 2A). Figure 1 illustrates this change in training distribution, when delineation of physiological and race-pace zones is visualized. It demonstrates the increase in volume at higher intensities over the season very clearly.

In Jones et al[11]'s analysis of the sub 2-hour marathon attempt group, the authors reported comparable physiological values to those in this athlete. Both our subject and Jones' group had relatively modest VO_2max by elite endurance standards (73.5 vs 71.0 [5.7] $mL{\cdot}kg{\cdot}min^{-1}$). Similar values between the subject and the group are also seen for vLT1 and vLT2 (18.3 vs 18.9 [0.4] $km{\cdot}h^{-1}$ and 20.3 vs 20.2 [0.6] $km{\cdot}h^{-1}$). The athlete in this study demonstrated greatest difference to the group studied above in RE submaximally and at 21 $km{\cdot}h^{-1}$ (193 vs 189 [14] $mL{\cdot}kg^{-1}{\cdot}km^{-1}$ and 199 vs 188 [20] $mL{\cdot}kg^{-1}{\cdot}km^{-1}$). The training data provided by this case study demonstrates an insight into how this physiological profile seen may be attained.

This work has highlighted the fact that elite performance does not require exceptional physiological characteristics across all of the 3 previously mentioned. Jones et al[11]'s testing showed that fastest athletes in the group were able to maintain approximately 96% of LT2 for marathon distance with very consistent running economies at increasing paces and exceptional fractional utilization of oxygen. Interestingly, the athlete in this case study displayed a similar metabolic profile to runners competing at significantly longer distances, only running economy being different. Whether this is common to world-class runners of shorter distances remains to be shown. Future work may include parameters, such as maximal sprint speed, power, and reactive strength, to provide further clarity to profiles compatible with world-class performance at different distances.

The results of this study are at odds with a polarized approach being the most effective way of improving performance. However, a number of considerations may help to explain. First, we have focused solely on running the weight-bearing nature of running and technical, biomechanical, and neuromuscular considerations associated with this may differentiate it from other sports. Second, this athlete demonstrated a polarized training block for 6 weeks leading into competition. It seems to be the result of increasing specificity of training around paces relative to target performance per the coaches express intention. Indeed, some other studies have found this specific periodization trend in elite distance runners, involving a switch from a more pyramidal TID during the preparatory periods to a more polarized TID during the competitive period.[12]

Practical Applications

Further work, which relates elite performance to observed physiological profiles, may allow for training to be informed more and more by physiological parameters in athletes such as these to allow for more precise prescription and training analysis. Longer term studies observing physiological fluctuation, tracked against performance fluctuation, may provide further value.

Table 2 Training Week Examples in the Early Season and the Competitive Phase

Day	Early season	Competitive phase
Monday	AM 60 min easy PM 30 min easy	AM 60 min easy PM 30 min easy
Tuesday	AM 8 × 1 km (60 s rest) PM 30 min easy	Track: 4 × 1600 (2 min rest) 10 k pace 6 × 400 (30 s rest) 3 k–5 k pace
Wednesday	AM 60 min easy PM 30 min easy	AM 60 min easy PM 30 min easy
Thursday	AM 9 km threshold (heart rate guided) PM 30 min easy	AM 9 km threshold PM 30 min easy
Friday	AM 60 min easy PM 30 min easy	AM 60 min easy
Saturday	AM Hilly 7.2 km threshold PM 30 min easy	AM 6 × 800 m hills (jog back) 5 k effort PM 30 min easy
Sunday	AM 105 min easy	AM 100 min easy

Conclusion

This study highlights the consistency of training over a 52-week period for a world-class athlete. Greater physiological polarization is seen in the competitive phase of the season, but at no other point. Taken alone this could potentially suggest that peak performance was achieved via a polarized training approach but, as we have shown, over the full 52 weeks the athlete followed a pyramidal distribution with significant volumes performed around threshold. This is consistent with recent papers showing that endurance running success is the result of years of consistent training, which includes high volumes of easy running and continuous threshold runs.[2,10]

References

1. Seiler KS, Kjerland GO. Quantifying training intensity distribution in elite endurance athletes: is there evidence for an “optimal” distribution? *Scand J Med Sci Sports*. 2006;16(1):49–56. PubMed ID: 16430681 doi:10.1111/j.1600-0838.2004.00418.x
2. Casado A, Hanley B, Ruiz-Perez LM. Deliberate practice in training differentiates the best Kenyan and Spanish long-distance runners. *Eur J Sport Sci*. 2020;20(7):887–895. PubMed ID: 31724902 doi:10.1080/17461391.2019.1694077
3. Stoggl T, Sperlich B. Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. *Front Physiol*. 2014;5:33. PubMed ID: 24550842 doi:10.3389/fphys.2014.00033
4. Kenneally M, Casado A, Santos-Concejero J. The effect of periodization and training intensity distribution on middle- and long-distance running performance: a systematic review. *Int J Sports Physiol Perform*. 2018;13(9):1114–1121. PubMed ID: 29182410 doi:10.1123/ijspp.2017-0327
5. Seiler SaT E. Intervals, threshold and long slow distance: the role of intensity and duration in endurance training. *Sports Science*. 2009;13:32–53.
6. Rosenblat MA, Perrotta AS, Vicenzino B, Polarized vs. Threshold training intensity distribution on endurance sport performance: a systematic review and meta-analysis of randomized controlled trials. *J Strength Cond Res*. 2018;33(12). doi:10.1519/JSC.0000000000002618
7. Kenneally M, Casado A, Gomez-Ezeiza J, Santos-Concejero J. Training intensity distribution analysis by race pace vs. physiological approach in world-class middle- and long-distance runners. *Eur J Sport Sci*. 2021;21(6):1–8. doi:10.1080/17461391.2020.1773934
8. Tjelta LI. The training of international level distance runners. *Int J Sports Sci Coach*. 2016;11(1):122–134. doi:10.1177/1747954115624813
9. Enoksen E, Tjelta AR, Tjelta LI. Distribution of training volume and intensity of elite male and female track and marathon runners. *Int J Sports Sci Coach*. 2011;6(2):273–293. doi:10.1260/1747-9541.6.2.273
10. Casado A, Hanley B, Santos-Concejero J, Ruiz-Perez LM. World-class long-distance running performances are best predicted by volume of easy runs and deliberate practice of short-interval and tempo runs [published online April 30, 2019]. *J Strength Cond Res*. doi:10.1519/JSC.0000000000003176
11. Jones AM KB, Clark IE, Rice HM, Fulkerson E, Wylie LJ, Wilkerson DP, Vanhatalo A, Wilkins BW. Physiological demands of running at 2-hour marathon race pace. *J Appl Physiol*. 2020;130(2). doi:10.1152/japplphysiol.00647.2020
12. Leif Inge T. A longitudinal case study of the training of the 2012 European 1500 m track champion. *Int J Appl Sports Sci*. 2013;25(1):11–18. doi:10.24985/ijass.2013.25.1.11

International Experience

Institution: Trinity College Dublin, Department of Anatomy

City: Dublin (Ireland) **Duration (weeks):** 16

Topic: Training prescription and periodisation for elite endurance sport

Type of collaboration: Teaching and examination

10th May 2022

Dear Mr. Kenneally,

I wish to thank you for your academic contributions to our MSc. in Sports and Exercise Medicine programme this semester (January – May 2022). During that time you delivered lectures in module AN7109 (Sports Science) covering training prescription and periodization in elite endurance sport. In addition you oversaw practical classes in module AN7108 (MSK Rehabilitation) covering musculoskeletal injury assessment. These lectures and practical sessions were delivered face-to-face to our class of 9 international MSc. Students. You also acted as an examiner of the student's laboratory and clinical skills during our end-of-semester station based OSCE exam.

We are extremely grateful for your continued support of our MSc. programme and we look forward to future collaborations in Sports Medicine teaching and research.

Yours sincerely,

Neil Fleming, PhD.,

Human Performance Laboratory,

Department of Anatomy,

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Ethics approval

GIZAKIEKIN ETA HAUEN LAGIN ETA DATUEKIN EGINDAKO IKERKETEI BURUZKO ETIKA BATZORDEAREN (GIEB-UPV/EHU) TXOSTENA

Mª Jesús Marcos Muñoz andreak, Universidad del País Vasco/Euskal Herriko Unibertsitateko (UPV/EHU) GIEBeko idazkari gisa,

ZIURTATZEN DU

Ezen gizakiekin egindako ikerkuntzaren etika batzorde honek, GIEB-UPV/EHU, (2014/2/17ko 32. EHAA) **Balioetsi duela** ondoko ikertzailearen proposamen hau:
Jordan Santos Concejero andreak, M10_2017_178, honako ikerketa proiektu hau egiteko:
"Aspectos fisiológicos y de entrenamiento de corredores de media y larga distancia de nivel internacional"

Eta aintzat hartuta ezen

1. Ikerketa justifikatuta dago, bere helburuei esker jakintza areagotu eta gizarteari onura ekarriko baitio, ikerlanak lekartzakeen eragozpen eta arriskuak arrazoizko izanik.
2. Ikertzaile taldearen gaitasuna eta erabilgarri dituzten baliabideak aproposak dira proiektua gauzatzeko.
3. Ikerketaren planteamendua bat dator era honetako ikerkuntza egin ahal izateko baldintza metodologiko eta etikoekin, ikerkuntza zientifikoaren praktika egokien irizpideei jarraiki.
4. Indarreko arauak betetzen ditu, ikerketa egin ahal izateko baimenak, akordioak edo hitzarmenak barne.

Aldeko Txostena eman du 2017ko azaroaren 23an egin duen bileran (94/2017akta) aipatutako ikerketa proiektua ondoko ikertzaileek osatutako taldeak egin dezan:

Jordan Santos Concejero
Mark Kenneally
Arturo Casado Alda

Eta halaxe sinatu du Leioan, 2017ko azaroaren 24an

INFORME DEL COMITÉ DE ÉTICA PARA LAS INVESTIGACIONES CON SERES HUMANOS, SUS MUESTRAS Y SUS DATOS (CEISH-UPV/EHU)

Mª Jesús Marcos Muñoz como Secretaria del CEISH de la Universidad del País Vasco/Euskal Herriko Unibertsitatea (UPV/EHU)

CERTIFICA

Que este Comité de Ética para la Investigación con Seres Humanos, CEISH-UPV/EHU, BOPV 32, 17/2/2014,
Ha evaluado la propuesta del investigador:
D. Jordan Santos Concejero, M10_2017_178, para la realización del proyecto de investigación: *"Aspectos fisiológicos y de entrenamiento de corredores de media y larga distancia de nivel internacional"*

Y considerando que,

1. La investigación está justificada porque sus objetivos permitirán generar un aumento del conocimiento y un beneficio para la sociedad que hace asumibles las molestias y riesgos previsibles.
2. La capacidad del equipo investigador y los recursos disponibles son los adecuados para realizarla.
3. Se plantea según los requisitos metodológicos y éticos necesarios para su ejecución, según los criterios de buenas prácticas de la investigación científica.
4. Se cumple la normativa vigente, incluidas las autorizaciones, acuerdos o convenios necesarios para llevarla a cabo.

Ha emitido en la reunión celebrada el 23 de noviembre de 2017 (acta 94/2017), **INFORME FAVORABLE** a que dicho proyecto de investigación sea realizado, por el equipo investigador:

Jordan Santos Concejero
Mark Kenneally
Arturo Casado Alda

Lo que firmo en Leioa, a 24 de noviembre de 2017

Mª Jesús Marcos Muñoz
GIEB-UPV/EHUko idazkari teknikoa
Secretaria Técnica del CEISH-UPV/EHU

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Congress Presentation

Oral presentation:

Training Intensity Distribution analysis by Race Pace Approach in World-Class distance runners

XXIII annual Congress of the European College of Sports Science (Dublin, Ireland). From 04/07/2018 to 07/07/2018

EUROPEAN COLLEGE OF SPORT SCIENCE

Feldblumenweg 26
50858 Cologne

GERMANY

VAT-ID: DE251715668 - St.Nr.: 223/5905/0216
register of associations: VR12508

Dublin, 11.07.2018 - 12:32:46

Confirmation of Presentation

This is to certify that the following title has been presented at the 23rd Annual Congress of the European College of Sport Science between 4 - 7 July 2018 in Dublin - Ireland:

Mark Kenneally

University of The Basque Country
Portal de Lasarte 71
01007 Vitoria-Gasteiz, Spain

Abstr.-ID: 2762, Presentation format: Oral , Session name: OP-PM08 - PERIODIZED AND HIT TRAINING
Title: Training Intensity Distribution analysis by Race Pace Approach in World-Class distance runners.
Authors: Kenneally, M., Casado Alda, A., Santos-Concejero, J.
Institution: University of The Basque Country
Presentation date: 04.07.2018, 15:30, Lecture room: The Liffey B, No: 5

Institute for Sport and Health, UCD & Ulster University School of Sport

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Other contributions

Kenneally M, Casado A, Santos-Concejero J. Training Intensity Distribution analysis by Race Pace Approach in World-Class distance runners. Book of Abstracts 23th annual Congress of the European College of Sport Science; Murphy M, Boreham C, De Vito G, Tsolakidis E (Eds.) SporTools GmbH, Feldblumenweg (Germany). 89-90. 2018

23rd Annual Congress of the

EUROPEAN COLLEGE OF SPORT SCIENCE

4th - 7th July 2018, Dublin – Ireland

BOOK OF ABSTRACTS

Edited by:
Murphy, M., Boreham, C., De Vito, G., Tsolakidis, E.

Hosted by
Hosted by University College Dublin & Ulster University

ISBN 978-3-9818414-1-1

biomotor ability. This trial examined the effects of a high-intensity functional circuit training (HIFCT) program on motor function and motivation to exercise in healthy, untrained adults.
METHODS: Thirty-three physically inactive participants (25±5 yrs, 12 males) were randomly allocated to two groups exercising for a period of six weeks. The intervention group (HIFCT, n=20) 3×/week performed functional whole-body exercises (e.g. Squats, Step-Ups, Burpees) in a circuit format. Each 15-minute workout was composed of repetitive 20s all-out bouts with 10s breaks. In the comparison group (moderate aerobic exercise, MAE, n=13), the participants walked 3×/week for 50 minutes at moderate intensity. Motor outcomes measured were cycling endurance capacity (respiratory threshold, maximum work load), maximum strength (leg and chest press), postural control (force plate), and jump capacity (counter-movement jump, single leg hop for distance). Additionally, exercise motivation was assessed using the self-concordance index.
RESULTS: In comparison to MAE, HIFCT enhanced maximum leg strength (between-group difference of relative pre-post changes of 5.0%), shoulder strength (7.6%), endurance workload (5.0%; p<.05), as well as motivation to exercise (+5.5 points on the self-concordance index (p<.05). No between-group differences were found for postural control and jump capacity (p>.05).
CONCLUSION: Despite considerably shorter training duration, HIFCT increases motor function and motivation to exercise more effectively than MAE. Further research should investigate the long-term adherence to the program and its effectivity in other settings.

EVALUATING THE INTERNAL RESPONSE TO REPEATED-SPRINT TRAINING USING DIFFERENTIAL RPE: A PRELIMINARY INVESTIGATION IN SOCCER PLAYERS

MCLAREN, S.J., TAYLOR, J.M., MACPHERSON, T.W., SPEARS, I.R., WESTON, M.
TEESSIDE UNIVERSITY

INTRODUCTION: Changes in the internal response to an external training stimulus may be indicative of an athlete's fitness or fatigue. Differential ratings of perceived exertion (dRPE) enhance the precision of internal load quantification (Weston et al., 2015), yet little is known of how these measures change over a period of training adaptation. We therefore aimed to evaluate the within- (i.e. set-to-set) and between-session changes in dRPE across a repeated-sprint training (RST) intervention that was successful for improving a range of fitness components in soccer players (Taylor et al., 2016).
METHODS: Fifteen semi-professional soccer players completed 6 RST sessions over a 2-week period. The training programme consisted of 3 (sessions 1–3) or 4 (sessions 4–6) sets of 7 maximal effort sprints, with 20 sec and 4 min recovery between sprints and sets, respectively. Players were assigned to either a straight-line (n = 8; 30-m) or change of direction (n = 7; 2 × 10-m with a 180° turn) training group. Heart rate (HR; presented as % maximum heart rate) was recorded throughout each session and dRPE (presented in arbitrary units) for breathlessness (RPE-B) and leg muscle exertion (RPE-L) were collected via the CR100 scale ~2 min after each set. Data were analysed using mixed effects linear models, with magnitude-based inferences subsequently applied.
RESULTS: Mean ± SD set dRPE and HR were 47 ± 10 (hard) for RPE-B, 39 ± 9 (somewhat hard) for RPE-L, and 79 ± 7%. The difference between RPE-B and RPE-L was possibly moderate (8; ±90% confidence limits 7). Within-session changes in RPE-B were large in session 1 (15 per set; ±2), moderate in sessions 2 to 5 (7 to 9; ±2), and small in session 6 (6; ±2). For RPE-L, within-session changes were large in session 1 (15; ±3) and moderate in sessions 2 to 6 (7 to 8; ±2). The within-session changes in HR were trivial in sessions 1 to 5 (1 to 2 % points per set; ±1) and small in session 6 (2; ±3). When compared with session 1, the magnitude of within-session changes was substantially lower (small to moderate differences) in session 2 to 6 for RPE-B (-5 to -9 per set; ±2) and RPE-L (-6 to -8; ±2). No substantial between-session differences were evident for within-session changes in HR (0 to 1 % points per set; ±1).
CONCLUSION: Changes in dRPE, but not HR, are evident following a 6-week RST intervention that improved the fitness of soccer players, with the magnitude of within-session increments reducing across the programme. These changes could reflect training-induced adaptations, thus providing evidence for the sensitivity and usefulness of dRPE for monitoring training in soccer. Finally, players perceive the demands of RST to be greater for central, rather than peripheral, exertion, which may allude to specific training-induced adaptations. Relations between dRPE and training outcomes therefore warrant further investigation.
REFERENCES: Weston et al. (2015). J Sci Med Sport, 18(6), 704–708.
Taylor et al. (2016). Int J Sports Physiol Perform, 11(8), 998–1004.

TRAINING INTENSITY DISTRIBUTION ANALYSIS BY RACE PACE APPROACH IN WORLD-CLASS DISTANCE RUNNERS.

KENNEALLY, M., CASADO ALDA, A., SANTOS-CONCEJERO, J.
UNIVERSITY OF THE BASQUE COUNTRY

INTRODUCTION: Optimal Training Intensity Distribution (TID) in endurance running remains a much debated topic (1,2). The description of training intensity zones has classically been done using physiological parameters (2), and ranges from 3-7 zones within the literature (2). A recent review by the current authors (1) has proposed a novel way to describe training intensity zones. The zones are based on proportions of an athletes actual or target race pace. The rationale for this approach is based in the notion that race pace itself represents the intensity which optimally stresses the relevant physiological systems at any given point in time. Thus the aim of this paper was to analyse the training of a group of world-class athletes over a 12 month period, using this approach to identify whether their training is organised into zones as described.
METHODS: We took the training logs of both the male and female athletes and organised the data into 5 zones based on percentages of race pace, which were chosen arbitrarily. Volume, number of sessions and time spent in each zone was calculated. The analysis spanned all traditional phases of a training cycle; general preparatory, specific preparatory and competitive, so the data was further analysed based on these phases. Physiological and anthropometric data were also collected three times over the timeframe studied in a number of athletes, and where possible physiological zones were created and compared to the race-pace based zones. Session intention was also recorded.
RESULTS: The analysis showed that when the training of this group of elite distance runners is considered relative to their race pace, a pyramidal type training intensity distribution is seen, regardless of phase of training. This pyramidal distribution was also preserved across athletes competing at different race distances, ranging from 800m to 10000m. However, the absolute training intensities of this group were similar for athletes competing over different distances, and as a result, differences were seen in the volumes in respective relative zones. Longer distance athletes (5-10km) tended to have more volume in their higher relative intensity zones than shorter distance athletes (800-1500m), although both preserved pyramidal distributions.
CONCLUSION: This study demonstrates that Training Intensity Distribution can be considered relative to race pace as a valid method of analysis. It also identifies relative differences in the training of longer and shorter distance athletes, despite similar absolute training. The zones used in this study were arbitrarily chosen and further work is required to optimise what percentage of race pace should delineate

these zones. Further study, focussing on comparison of the effect of physiological zones vs race-pace based zones on physiological parameters and performance, would also improve the understanding of this topic.

Oral presentations

IS-EX02 ECSS-JSPFSM exchange symposium: Skeletal muscle as an endocrine organ -20 years of myokines

EVIDENCE FOR ACUTE CONTRACTION-INDUCED MYOKINE SECRETION BY C2C12 MYOTUBES

FURUICHI, Y.

TOKYO METROPOLITAN UNIVERSITY

Myokines have received attention as secretory factors in skeletal muscle cells and are related to exercise-induced health benefits in various organs. Myokine secretion is thought to be regulated by muscle contraction, but this hypothesis has not been confirmed. We sought to present evidence that acute contractions induced myokine secretion and to investigate the secretory mechanism of skeletal muscle cells.

We used murine-derived C2C12 skeletal muscle cell line to eliminate contamination with proteins produced by non-muscle cells. Cultured myotubes were contracted by electrical stimulation systems established by our group (Manabe et al. 2012), and secreted proteins in conditioned media were compared between basal and contracted conditions. Importantly, we noticed that changes in the cell culture medium unexpectedly triggered the release of large amounts of proteins from the myotubes, and these proteins obscured the contraction-induced myokine secretion. Once protein release was abolished, the secretion of interleukin-6 (IL-6), the best-known regulatory myokine, increased in response to a 1-hour contraction evoked by electrical stimulation.

We used pharmacological inhibitors of muscle contraction and examined whether contraction-induced IL-6 secretion disappeared following treatment with these inhibitors to identify the specific mechanism regulating contraction-induced IL-6 secretion in skeletal muscle cells. Contraction-induced IL-6 secretion was inhibited by EGTA, which chelates intracellular calcium, while the blockage of physical movement by the addition of BTS, a specific inhibitor of myosin ATPase, did not inhibit IL-6 secretion. Thus, calcium flux, rather than contraction itself, triggers contraction-induced IL-6 secretion.

Since we established the experimental conditions for secretion induced by acute contraction, we investigated whether the secretion of previously reported myokines was regulated by muscle contraction. IL-15 secretion by C2C12 myotubes increased in response to acute contraction. Surprisingly, contraction-induced IL-15 secretion was completely abolished by the BTS. Based on these data, IL-15 secretion is regulated by a different mechanism than IL-6 secretion. Our established experimental condition is suitable not only for the discovery of novel contraction-induced myokines but also for the dissection of the regulatory mechanism underlying myokine secretion.

We concluded that acute muscle contraction apparently promotes the secretion of some myokines, and our newly established experimental model will enable researchers to adopt a proteomic approach to identify new myokines secreted in response to muscle contraction. The identification of new myokines and an understanding of their regulatory mechanisms will be useful in the field of sports and health sciences.

ROLE OF LOCAL STEROIDOGENESIS IN SKELETAL MUSCLE

AIZAWA, K.

INSTITUTE OF SPORT

INTRODUCTION: The plasticity of skeletal muscle facilitates adaptation to various stimuli. Sex steroid hormones play critical roles in regulation of metabolism and function in skeletal muscle. Skeletal muscle has recently been identified as an endocrine organ. Sex steroid hormones are produced by various peripheral target tissues including the kidney, liver, and brain in addition to endocrine organs such as the testis or ovary.

METHODS: Sex steroid hormones are synthesized from cholesterol by steroidogenic enzymes, such as 3β-hydroxysteroid dehydrogenase , and 17β-HSD, with testosterone being irreversibly converted to estrogen by aromatase cytochrome P450 . Testosterone is also converted into its bioactive metabolite dihydrotestosterone by 5α-reductase.

RESULTS: We demonstrated that skeletal muscle containes these steroidogenic enzymes to synthesize sex steroid hormones from circulating dehydroepiandrosterone or testosterone and exercise activates local steroidogenesis in skeletal muscle.

CONCLUSION: Thus, local steroidogenesis in skeletal muscle may play an important role in the plasticity of skeletal muscle. This session focuses on the local steroidogenesis of skeletal muscle and discusses the physiological significance of the sex steroid hormone network of circulation and skeletal muscle.

MUSCLE-ORGAN CROSS-TALK: THE ROLE OF MYOKINES IN DIABETES AND CANCER

PEDERSEN, B.

RIGSHOSPITALET

We have suggested that cytokines and other peptides that are produced, expressed and released by muscle fibres and exert either autocrine, paracrine or endocrine effects should be classified as myokines. The finding that the muscle secretome consists of several hundred secreted peptides provides a conceptual basis for understanding how muscles communicate with other organs, such as adipose tissue, liver, pancreas, bones and brain. However, some myokines exert their effects within the muscle itself. Thus, myostatin, LIF, IL-6 and IL-7 are involved in muscle hypertrophy and myogenesis, whereas BDNF and IL-6 are involved in AMPK-mediated fat oxidation. IL-6 also appears to have systemic effects on the liver, adipose tissue, and the immune system, and mediates crosstalk between intestinal L cells and pancreatic islets. Other myokines include the osteogenic factors IGF-1 and FGF-2; FSTL-1, which improves the endothelial function of the vascular system; and the PGC-1α-dependent myokine irisin, which drives brown-fat-like development. Studies in the past few years have identified myokines, which may influence cancer cell growth. Many proteins produced by skeletal muscle are dependent upon contraction; therefore, physical inactivity probably leads to an altered myokine response, which could provide a potential mechanism for the association between sedentary behaviour and many chronic diseases.