



Monitorización y estudio de las relaciones entre la carga de entrenamiento, la producción de fuerza, la fatiga y el rendimiento en corredores de alto nivel

Monitoring and study of the relationships between training load, force production, fatigue and performance in high-level distance runners



TESIS DOCTORAL INTERNACIONAL [INTERNATIONAL PHD THESIS](#)

CARLOS BALSALOBRE-FERNÁNDEZ





Departamento de Educación Física, Deporte y Motricidad Humana
Department of Physical Education, Sport and Human Movement

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Tesis Doctoral Internacional por *International PhD Thesis by*

Carlos Balsalobre-Fernández

Directores Supervisors

Carlos M^a Tejero-González, PhD.

Juan del Campo-Vecino, PhD.

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Conflictos de interés *Conflicts of interest*

El autor declara que no tiene ningún conflicto de interés. El autor no recibió ninguna financiación y no está directa o indirectamente relacionado con el instrumental usado en la presente investigación.

El autor declara que la presente Tesis Doctoral es un trabajo original.

La presente Tesis Doctoral siguió los procedimientos establecidos en la Declaración de Helsinki y fue aprobada por el Comité de Ética de la Universidad Autónoma de Madrid, España (CEI-45-889).

The author declares that he has no conflicts of interest. The author has not received any financial reward or otherwise, nor is he directly or indirectly related to the instruments used in this manuscript.

The author declares that the present PhD Thesis is original.

The study was carried out in accordance to the Helsinki's declaration and was approved by the ethics committee at Autonomous University of Madrid, Spain (CEI-45-889).

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In the area of sports science, it is common to be asked about what is your sport, because usually students and researchers have been related, one way or another, with some specialty. In this regard, I wish to heartily thank my karate teacher Ángel Redondo. You instilled in me the love of the sport and training, and the motivation to undertake this adventure goes back to those times when the karate-gi was more than a clothing for me. I have not practice Karate for years now, but I will be karateka for life.

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Resumen *Abstract*

Antecedentes: La monitorización de las cargas de trabajo, del grado de fatiga y el rendimiento físico se considera clave para optimizar el proceso de entrenamiento en deportistas de alto nivel. Sin embargo, hasta donde sabemos, no existen estudios que analicen las relaciones entre la carga de entrenamiento, la producción de fuerza, el grado de fatiga y el rendimiento en competición en corredores de mediofondo y fondo de alto nivel a lo largo de una temporada.

Objetivo: La presente Tesis Doctoral tuvo 3 objetivos: (1) Analizar la relación entre la carga de entrenamiento, los niveles de CMJ, cortisol libre en saliva y el rendimiento en competición durante toda una temporada en corredores de mediofondo y fondo de alto nivel; (2) Estudiar la evolución de la fuerza de los miembros inferiores durante toda la temporada, así como su relación con los niveles medios de carga de entrenamiento y cortisol libre en saliva; (3) Analizar los efectos de la competición más importante del año en el CMJ, los niveles de cortisol

Background: Monitoring training loads, the degree of fatigue and physical performance is considered key to optimize the process of training in high-level athletes. However, to our knowledge, no studies have analyzed the relationship between training load, force production, the degree of fatigue and performance in high-level middle and long-distance runners throughout a season.

Purpose: This PhD Thesis has three purposes: (1) To analyze the relationship between training load, CMJ height, salivary free cortisol and performance during a season in high-level middle and long-distance runners; (2) To study the time-course of the lower limbs force production during the season, and its relationship with the average levels of training load and salivary free cortisol; (3) To analyze the effects of the most important competition of the year on CMJ height, salivary free

libre en saliva y el RPE, así como la relación entre dichas variables.

Método: El RPE, los kilómetros recorridos, la zona de entrenamiento (diariamente), el CMJ, el cortisol libre en saliva (semanalmente), la producción de fuerza en media sentadilla, el sprint de 50m (5 veces) y el rendimiento en competición fueron medidos durante toda una temporada en un grupo de corredores de mediofondo y fondo de alto nivel (12 hombres, 3 mujeres; edad=26.3±5.1 años). Adicionalmente, el CMJ y el cortisol libre en saliva (antes y después de la carrera) y el RPE (después de la carrera) se midieron en la competición más importante del año.

Resultados: (1) Los niveles de cortisol libre en saliva correlacionaron significativamente con el CMJ ($r = -0.777$) y el RPE ($r = 0.551$). Además, los niveles de CMJ (+8.9%) y RPE (-17.6%) medidos antes de la mejor competición de la temporada fueron significativamente diferentes a los valores medidos antes de la peor competición de la temporada; (2) El RPE correlacionó significativamente con la producción de fuerza en media sentadilla ($r = -0.602, -0.650$) y el sprint de 50m ($r = 0.560$). Los atletas no variaron sus niveles de producción de fuerza en media sentadilla a lo largo de la temporada, con

cortisol levels and RPE, and the relationship between these variables.

Methods: Session-RPE, running km, training zone (daily), CMJ, salivary free cortisol (weekly), force production in half squat, 50m sprint (5 times) and performance in competition were measured over a full season in a group of high-level middle and long-distance runners (12 men, 3 women, age = 27.6 ± 5.1 years). Additionally, the CMJ and salivary free cortisol (before and after the race) and RPE (after the race) were measured in the most important competition of the year.

Results: (1) The levels of salivary free cortisol correlated significantly with the CMJ ($r = -0.777$) and RPE ($r = 0.551$). Furthermore, levels of CMJ (+ 8.9%) and RPE (-17.6%) measured before the best competition of the season were significantly different to those values measured before the worst race of the season; (2) The RPE was significantly correlated with force production in half squat ($r = -0.602, -0.650$) and 50m sprint ($r = 0.560$). The athletes did not change their levels of force production in half squat over the season, with

la excepción de la RFD, que disminuyó significativamente (-30.2%); (3) La pérdida de CMJ después de la carrera más importante del año correlacionó significativamente con el incremento del cortisol ($r = 0.782$) y los niveles de RPE ($r = 0.762$) medidos después de la misma.

Conclusiones: La monitorización sistemática del CMJ y el RPE puede aportar información útil sobre el grado de fatiga y el estado de forma competitiva de los corredores de mediofondo y fondo de alto nivel de una manera sencilla y no invasiva. El entrenamiento de fuerza llevado a cabo por los atletas, con cargas en torno a 15-20RM y con 1-2 sesiones semanales puede no ser un estímulo suficiente para la mejora de la producción de fuerza en estos deportistas.

the exception of the RFD, which decreased significantly (-30.2%); (3) The loss of CMJ after the most important race of the year correlated significantly with the increase of cortisol ($r = 0.782$) and RPE levels ($r = 0.762$) measured after that race.

Conclusions: *Monitoring the CMJ and RPE can provide useful information about the degree of fatigue and the competitive preparedness of high-level middle and long-distance runners in a simple, noninvasive, systematic way. The strength training performed by the athletes, with loads around 15-20RM and 1-2 sessions per week may not be an adequate stimulus to improve their force production.*

Lista de publicaciones *Publications list*

Artículo 1 *Paper 1*: Balsalobre-Fernández C, Tejero-González CM, del Campo-Vecino J. Relationships between Training Load, Salivary Cortisol Responses and Performance during Season Training in Middle and Long Distance Runners. PLoS One. 2014;9(8):e106066.

Artículo 2 *Paper 2*: Balsalobre-Fernández C, Tejero-González CM, del Campo-Vecino J. Seasonal strength performance and its relationship with training load on elite runners. J Sport Sci Med. 2015;14(1); 9-15.

Artículo 3 *Paper 3*: Balsalobre-Fernández C, Tejero-González CM, Del Campo-Vecino J. Hormonal and Neuromuscular Responses to High Level Middle and Long-Distance Competition. Int J Sports Physiol Perform. 2014;9(5):839-44.

Abreviaturas *Abbreviations*

ANOVA: análisis de la varianza *analysis of variance*

CMJ: salto vertical con contramovimiento *countermovement jump*

ELISA: ensayo por inmunoabsorción ligado a enzimas *enzyme-linked immunosorbent assay*

IMC/BMI: índice de masa corporal *body mass index*

PMP/MPP: potencia media propulsiva *mean propulsive power*

RFD: índice de producción de fuerza *rate of force development*

RPE: índice de esfuerzo percibido *rate of perceived effort*

RM: Repetición Máxima *Repetition Maximum*

RFEA/RSAF: Real Federación Española de Atletismo *Royal Spanish Athletics Federation*

T1500: marca personal en 1500m *personal best on 1500m*

T10000: marca personal en 10000m *personal best on 10000m*

TRIMPs: impulsos de entrenamiento *training impulses*

VMP/MPV: velocidad media propulsiva *mean propulsive velocity*

VO2Máx: consumo máximo de oxígeno *maximum oxygen uptake*

Prólogo *Foreword*

Entiendo la investigación como un proceso de descubrimiento, de avance, de innovación pero, sobre todo, de difusión. La inquietud última de mi tarea investigadora siempre ha sido la búsqueda, desde una aproximación científica, de unas aplicaciones prácticas reales que puedan servir a entrenadores y deportistas para mejorar su proceso de entrenamiento. La presente Tesis Doctoral ha tenido esta orientación desde el primer momento con el objetivo de aportar un pequeño grano en la optimización de los métodos de monitorización del entrenamiento de corredores de alto nivel.

Desgraciadamente, al menos en nuestro país, los corredores de alto nivel no tienen todas las ayudas y soporte tecnológico-científico deseables en estos tiempos de crisis. Si las conclusiones y aplicaciones prácticas que se desprenden de esta investigación pueden ser de alguna ayuda para el entrenamiento del atletismo de alto nivel, un deporte tan trascendental como descuidado, todo el trabajo habrá merecido la pena.

I understand research as a process of discovery, progress, innovation and, above all, sharing. The final concern of my research work has always been to find practical applications that coaches and athletes could use for improving their training methods, always from a scientific point of view. The present PhD Thesis has had this approach from the beginning with the aim of improving a little the knowledge about the optimization of the monitoring process on high-level distance runners.

Unfortunately, at least in our country, elite distance runners don't have appropriate financial, technological and scientific support because of these times of crisis. If the conclusions and practical applications that emerge from this research are of some help for high-level distance running training, a legendary but abandoned sport, all the work would be worth it.

1

Parte teórica *Theoretical Background*

“Fall seven times and stand up eight”

– Japanese proverb



Objeto de estudio de la investigación

Research topic



El proceso del entrenamiento deportivo de alto nivel implica conocer, evaluar y prescribir múltiples variables psico-fisiológicas [1-3]. En este sentido, dos líneas de investigación de máxima relevancia en el contexto del deporte de alto nivel son, por un lado, la determinación de los factores del entrenamiento que tienen una mayor relación con el rendimiento en tareas específicas de cada deporte y, por otro lado, la optimización del proceso de

The process of high-level sports training involves knowing, evaluating and prescribing multiple psychophysiological variables [1-3]. In this regard, two lines of research highly relevant in the context of high-level sport are, first, the determination of the most related factors with competitive performance, and second, the optimization of the training

entrenamiento mediante la cuantificación de las cargas y su relación con el estado de forma, la fatiga y el rendimiento de los deportistas.

En cuanto a los factores determinantes del rendimiento deportivo (en concreto, en las especialidades de mediofondo y fondo en atletismo), las evaluaciones del nivel del deportista y los métodos de entrenamiento se han centrado en variables relacionadas puramente con la resistencia, como el consumo máximo de oxígeno o la concentración de lactato en sangre tras una prueba de carrera [4-8]. No obstante, actualmente, multitud de autores resaltan la importancia de la fuerza y la potencia muscular en el rendimiento deportivo incluso en las especialidades de resistencia, pues sus beneficios parecen ser muy amplios [9-12]. Por ejemplo, el entrenamiento de fuerza ha mostrado incrementar el rendimiento en pruebas de resistencia a través de la mejora de la economía de carrera y de la potencia muscular, entre otras variables [13-15].

Por su parte, la cuantificación de las cargas de entrenamiento es sin duda una de las partes más importante del proceso de preparación deportiva, pues ello permite organizar, prescribir y optimizar los estímulos de entrenamiento para controlar

process by quantifying training loads and their relationship to the fitness, fatigue and performance of athletes.

As for the determinants of athletic performance (particularly in middle and long-distance running), assessments of the level of the athlete and the training methods have focused on variables related purely to endurance capacities, as the maximum oxygen uptake or blood lactate concentrations [4-8]. However, currently many authors emphasize the importance of muscular strength and power in athletic performance even in endurance specialities, since its benefits seem to be very large [9-12]. For example, strength training has been shown to increase endurance performance by improving running economy and muscle power, among other variables [13-15].

Meanwhile, quantifying training loads is certainly one of the most important parts of the training process, since it allows to organize, optimize and prescribe the training stimuli to control

el estado de forma de cada deportista y maximizar su rendimiento [1,4,16,17]. Además, gracias a la cuantificación de las cargas de entrenamiento podemos aproximarnos al conocimiento del grado de fatiga que cada sesión le produce a cada deportista, lo cual puede aportar información de vital importancia para prevenir lesiones o el síndrome de sobreentrenamiento [16,17].

La manera más adecuada de cuantificar la carga de entrenamiento es mediante indicadores internos al deportista [4,16,18]. Estos indicadores son variables biológicas que muestran la respuesta individual de cada deportista para una carga externa dada (por ejemplo, número de kilómetros corridos a la semana). En el entrenamiento de deportistas de resistencia de alto nivel, los indicadores más utilizados son el consumo de oxígeno, la frecuencia cardíaca (y el cálculo asociado de los llamados impulsos de entrenamiento o TRIMPs[17,19]) o los niveles de lactato en sangre [14,20-24]. Sin embargo, dichas variables sólo pueden medirse unas pocas veces a lo largo de la temporada, pues requieren materiales tecnológicos muy sofisticados, asistencia médica o laboratorios de fisiología del esfuerzo y, además, pueden suponer un estrés importante para los deportistas.

the fitness of each athlete and maximize their performance [1,4,16,17]. Also, quantifying training loads could help to know about the degree of fatigue that training sessions produce to each athlete, which can provide vital information to prevent injury or the overtraining syndrome [16,17].

The best way to quantify the training load is through internal indicators [4,16,18]. These internal indicators are biological variables that show the individual response of each athlete for a given external load (eg, number of running km per week). In high-level endurance sports, the most used indicators are oxygen consumption, heart rate (and the associated calculation of so-called training impulses or TRIMPs [17,19]) or blood lactate levels [14,20-24]. However, these variables can be measured only a few times throughout the season, as they require sophisticated technological materials, medical care or sport physiology laboratories, and also its measurement could be a major stress for the athletes.

Solucionando estas limitaciones, se han propuesto diversas opciones para valorar la carga de entrenamiento y el grado de fatiga de los deportistas de una manera no invasiva y prolongada en el tiempo [4,25-27]. Numerosos autores cuantifican la carga de entrenamiento mediante el uso de la percepción de esfuerzo (RPE, por sus siglas en inglés: rate of perceived exertion), siendo una variable psicológica y subjetiva que ha demostrado una gran capacidad para expresar el grado de esfuerzo que el entrenamiento le supone a los deportistas [28-31]. Además, en menor medida se está comenzando a valorar la capacidad de salto vertical como indicador del grado de fatiga neuromuscular, debido a las estrechas relaciones ($r>0.90$) que dicha habilidad ha mostrado tener con los valores de lactato y amonio en sangre después de diversos esfuerzos, principales indicadores biológicos de la fatiga[32] . Por último, la valoración del cortisol libre en saliva, hormona relacionada con la fatiga y el estrés, está siendo ampliamente utilizada gracias a su medición no invasiva y fácilmente administrable en el campo sin necesidad de personal e instrumental médico [3,33-35]. Dichas variables, inocuas para el deportista y fácilmente medibles en la propia pista de entrenamiento, pueden ser administradas

Solving these limitations, several options have been proposed to assess training loads and the degree of fatigue of athletes in a noninvasive, systematic way [4,25-27]. Numerous authors quantify training load through the use of the rate of perceived exertion (RPE), being a psychological and subjective variable that has shown great ability to show the level of exertion that a particular training produce to athletes [28-31]. Also, to a lesser extent the vertical jumping ability is being used as an indicator of neuromuscular fatigue, due to its close relationship ($r> 0.90$) with blood lactate and ammonia, key biological indicators of fatigue [32]. Finally, the assessment of salivary free cortisol, a hormone related to fatigue and stress, is being widely used due to its non-invasive, simple measurements which can be performed right in the track without medical supervision or laboratory instrumental [3,33-35] . These variables, safe for athletes and easily measured in real training situations, can be administered

a diario, lo cual puede ayudar a dar una visión cercana de la evolución del proceso de entrenamiento de los atletas.

Sin embargo, a pesar de que, por un lado, la producción de fuerza parece tener una importante relevancia en el rendimiento en actividades de carrera y que, por otro lado, la medición del RPE, el cortisol libre en saliva y el salto vertical han mostrado una alta capacidad para valorar la carga de entrenamiento y el grado de fatiga, no hemos sido capaces de encontrar estudios en la literatura científica que analicen las relaciones entre la capacidad de producir fuerza, la carga de entrenamiento, el grado de fatiga y el rendimiento competitivo en corredores de media y larga distancia de alto nivel, siendo este el objeto de estudio de la presente Tesis Doctoral. Así, cabe pensar que el conocimiento de dichas relaciones ayudará a entender los efectos que el entrenamiento de mediofondo y fondo tiene sobre la producción de fuerza y el grado de fatiga, así como a diseñar estrategias para optimizar el proceso de entrenamiento.

daily, which can help to give a closer look at the evolution of the training process of the athletes.

However, although, first, the force production seems to have an important role on running performance and, second, the measurement of RPE, salivary free cortisol and vertical jump height have demonstrated a high ability to assess training load and the degree of fatigue, we couldn't find papers on the scientific literature analyzing the relationship between the force production, training loads, the degree of fatigue and competitive performance in high-level middle and long-distance runner. This is the research topic of this PhD Thesis. Thus, increasing the knowledge about these relationships could help to understand the effects that high-level middle and long-distance training has on force production and the degree of fatigue, as well as to design strategies to optimize the training process.

Fuerza y rendimiento en mediofondo y fondo

Strength and performance in distance running



Importancia de la producción de fuerza en pruebas de mediofondo y fondo

Tradicionalmente, el entrenamiento de fuerza en especialidades de resistencia como las carreras de mediofondo y fondo de atletismo ha tenido una presencia muy limitada en los centros de entrenamiento. Aún hoy, la experiencia nos dice que su puesta en práctica es escasa, y en algunos momentos de la temporada incluso inexistente. Si bien los estímulos

Importance of force production in middle and long-distance running

Traditionally, strength training has had a very limited presence on the preparation of middle and long-distance runners. Even today, experience tells us that its implementation is scarce, and in some moments of the season, even non-existent. Although cardiovascular stimulus

cardiovasculares (ya sean continuos o intermitentes) deben ser la parte principal del entrenamiento en estas especialidades de resistencia[36-40], son múltiples las evidencias que demuestran que el entrenamiento de fuerza puede incrementar significativamente el rendimiento (entendiéndose como la marca realizada en una prueba específica de carrera) en corredores de media y larga distancia de distintos niveles, incluidos los de alto nivel [11,12,14,41-43]. De hecho, actualmente se sabe que la economía de carrera, la velocidad asociada al VO₂Máx o la potencia anaeróbica, variables en parte influenciadas por el rendimiento neuromuscular y, por tanto, por la capacidad de producir fuerza, son mejores predictores del rendimiento de los corredores de élite que otras pruebas de la función cardiovascular clásicas como el consumo máximo de oxígeno o el umbral de lactato[5,44-47].

El entrenamiento de fuerza es capaz de producir diversas adaptaciones morfológicas y neurológicas que aumentarían la capacidad de producir fuerza[10,48]. En cuanto a las adaptaciones morfológicas, el entrenamiento de fuerza puede inducir unos cambios beneficiosos en la arquitectura muscular, como un aumento de la hipertrofia (especialmente de las

(either continuous or intermittent) should be the main part of the training in endurance specialities [36-40], there are many evidences showing that strength training can significantly increase performance (i.e., the time to run a specific running event) in middle and long-distance runners, including high-level practitioners [11,12,14,41-43]. In fact, it is now known that running economy, the velocity associated with VO₂max and anaerobic power, variables partly influenced by neuromuscular performance and therefore by ability to produce force, are better predictors of elite running performance than other classic tests like the maximum oxygen consumption or lactate threshold [5,44-47].

Strength training can produce various morphological and neurological adaptations that increase the ability to produce force [10,48]. Regarding morphological adaptations, strength training can induce some beneficial changes in muscle architecture as increased hypertrophy (especially

fibras de tipo II), un incremento de la rigidez o stiffness del tendón o una modificación en el ángulo de penneación de las fibras musculares[46,49-51]. En cuanto a las adaptaciones neuromusculares, el entrenamiento de fuerza ha demostrado producir mejoras en el reclutamiento de las fibras rápidas, la sincronización de las unidades motoras, la coactivación agonista-antagonista o los reflejos espinales, entre otros factores[10,52-54]. De esta forma, el entrenamiento de fuerza es capaz no sólo de aumentar la producción de fuerza del músculo, sino también la velocidad a la que dicha fuerza se manifiesta [53,55-57]. En última instancia, todas esas mejoras en el sistema neuromuscular resultan en un incremento de la producción de potencia muscular, o lo que es lo mismo, en un aumento notable de la velocidad de ejecución del ejercicio ante una misma carga, lo cual implica una mayor capacidad de aplicar fuerza [58-60]. De esta forma, dado que en la inmensa mayoría de deportes se desplaza el propio peso corporal o el de un implemento de características específicas, el incremento de potencia muscular en el gesto deportivo supondrá una mayor velocidad de ejecución y, por lo tanto, un incremento del rendimiento físico [61,62]. Así, los beneficios que el entrenamiento de la

on type II fibers), an increase of tendon stiffness, or a change in the angle of pennation of the muscle fibers [46,49-51]. With respect to the neuromuscular adaptations, strength training has been shown to produce improvements in the recruitment of fast fibers, synchronization of motor units, the agonist-antagonist coactivation or spinal reflexes, among other factors [10,52-54]. Thus, strength training is able not only to increase the production of muscle strength but also the rate at which that force is manifested [53,55-57]. Ultimately, all these improvements in the neuromuscular system results in an increased production of muscle power, or what is the same, a significant increase in the movement velocity with the same load, which implies a greater ability to apply force [58-60]. Thus, given that the vast majority of sports aims to move the own body weight or an specific implement, the improvement of muscle power in competitive conditions will mean a higher movement velocity and therefore, an increase physical performance [61,62]. Thus, the positive effects that strength training

fuerza tiene sobre el rendimiento físico en diversos tipos de especialidades deportivas y poblaciones está fuera de toda duda [42,63-65].

De esta forma, en los últimos años diversos autores se han preocupado de investigar los posibles beneficios que el entrenamiento de fuerza puede tener sobre diversas variables relacionadas con el rendimiento en pruebas de mediofondo y fondo en deportistas de distintos niveles [11,12,66-68]. Específicamente, el entrenamiento de fuerza parece capaz de incrementar variables clave para el rendimiento en carrera como la velocidad al consumo máximo de oxígeno, la velocidad anaeróbica máxima o la economía de carrera, siendo esta última la que más atención está recibiendo en la literatura recientemente [11,12,14,44,46,47,69,70]. La economía de carrera corresponde al consumo de oxígeno que un atleta presenta ante una velocidad determinada de carrera [5,47,71]. Si se produce una mejora en la economía de carrera esto implica, por un lado, que dicho deportista es capaz de consumir menos oxígeno corriendo a la misma velocidad y, por otro lado, que con un mismo consumo de oxígeno puede correr más rápido. En otras palabras, la mejora de la economía de

produce on physical performance for different kinds of sports and populations is beyond any doubt [42,63-65].

Thus, in the past recent years several authors have studied the potential benefits that strength training can have on a number of variables related to middle and long-distance running performance on athletes with different training levels [11,12,66- 68]. Specifically, strength training seems able to increase key variables of running performance, like the velocity at maximal oxygen consumption, the maximum anaerobic speed or running economy, being the latter the one which is receiving more attention in the literature [11,12,14,44,46,47,69,70]. Running economy corresponds to the oxygen consumption produced at a given running speed [5,47,71]. If running economy is increased this implies, first, that the athlete is able to consume less oxygen running at the same speed, and, second, that with the same oxygen consumption he or she can run faster. In other words, improving the running economy

carrera incrementa la eficiencia del deportista. Así, la disminución del gasto energético para una velocidad dada supondrá una mayor capacidad para correr más rápido y durante más tiempo [5,72]. Por ello, la mejora de la economía de carrera es una adaptación muy deseada en las pruebas de mediofondo y fondo. De hecho, teniendo en cuenta que los atletas de alto nivel probablemente no puedan mejorar más su VO₂Máx o su umbral anaeróbico, habiendo llegado a su techo fisiológico [23,39,73,74], la mejora de la economía se ha convertido en una de las variables diana para el incremento del rendimiento en las pruebas de resistencia.

Por ejemplo, Storen et al. [15] estudiaron los efectos de 8 semanas de entrenamiento de fuerza sobre la economía de carrera a la velocidad asociada al 70% del VO₂Máx, así como sobre otras variables, en un grupo de corredores de 5000 m semi-profesionales. El estudio contó con dos grupos de 8 corredores cada uno: el control (C) y el experimental (E). El grupo E añadió a su rutina habitual 3 sesiones de entrenamiento de fuerza a la semana (consistente en 4 series de 4RM en sentadilla), mientras que el grupo C realizó únicamente su entrenamiento de

increases the efficiency of the athlete. Thus, the decrease in energy expenditure for a given speed will mean a greater ability to run faster and longer [5,72]. Therefore, improved running economy is a highly desired adaptation in middle and long-distance running. In fact, taking into account that elite athletes probably won't improve their VO₂max or anaerobic threshold, having already reached their maximal values [23,39,73,74], the improvement of running economy has become a target variable for endurance training.

For example, Storen et al. (2008) [15] studied the effects of 8 weeks of strength training on running economy at the speed associated with 70% VO₂max, as well as other variables, in a group of semi-professional 5000m runners. The study involved two groups of 8 participants each: control (C) and experimental (E). The E group added to their usual routine 3 sessions of strength training/week (consisting of 4 sets of 4RM in the squat exercise), while the C group performed exclusively their endurance

resistencia. Pasadas las 8 semanas, el grupo E mejoró significativamente su economía de carrera al 70% VO₂Máx, así como su RM y su producción de fuerza explosiva en sentadilla y el tiempo hasta la fatiga corriendo a su velocidad aeróbica máxima, mientras que el grupo C no mejoró significativamente ninguna variable estudiada. En la misma línea, Ramírez-Campillo et al.[42] estudiaron los efectos de un programa de entrenamiento de fuerza explosiva sobre el rendimiento en carrera en corredores de alto nivel (marcas personales en 1500m sobre 3min50s). Para ello, dividieron a un grupo de 36 atletas en 2 grupos: uno experimental, que realizó un entrenamiento pliométrico 2 veces por semana junto a sus sesiones convencionales de resistencia, y otro control, que hizo exclusivamente dicho entrenamiento de resistencia. Al cabo de 6 semanas de intervención, el grupo experimental aumentó significativamente el tiempo en el test de carrera de 2.4km, así como su salto vertical con contramovimiento (CMJ) y el sprint de 20 metros, mientras que el control mantuvo sus valores inalterados.

Se ha propuesto que el incremento de la economía de carrera producida por el entrenamiento de fuerza es debido fundamentalmente a mejoras en el sistema

training. After 8 weeks, the E group significantly improved their running economy at 70% VO_{2max} and its RM and explosive force production on squat, as well as the time to exhaustion at maximum aerobic speed, while the C group did not significantly improved any variable. Similarly, Ramirez-Campillo et al. [42] studied the effects of explosive strength training on running performance in high level runners (personal best in 1500m about 3min50s). To do this, they divided a group of 36 athletes into 2 groups: an experimental group who performed 2 sessions of plyometric training per week along with their conventional endurance training, and a control group, which performed exclusively their endurance training. After 6 weeks of intervention, the experimental group significantly increased the time in the 2.4km run test, its countermovement jump (CMJ) and the 20m sprint, while the control group did not improve any variable.

It has been proposed that the increase in running economy produced by strength training is primarily due to improvements in the neuromuscular

neuromuscular [5,44,68]. En concreto, el entrenamiento de fuerza produciría un mayor reclutamiento de fibras rápidas, mejoras en la sincronización de unidades motoras, una mayor producción de potencia muscular o un menor tiempo de apoyo en cada zancada [10,44]; adaptaciones que parecen ser importantes en la mejora del rendimiento en carrera [42,44,45,75]. En este sentido, se han observado mejoras en el rendimiento en carrera y en distintas pruebas neuromusculares como el salto vertical asociados a un incremento de la economía de carrera después de un programa de entrenamiento de fuerza, sin que se produjeran cambios en el VO₂Máx [68,76]. Sin embargo, dado el escaso número de investigaciones con deportistas de alto nivel, y la diversidad de los programas de entrenamiento de fuerza utilizados, son necesarios más estudios que ayuden a comprender bajo qué mecanismos y con qué características el entrenamiento de fuerza es capaz de mejorar el rendimiento en carrera. No obstante, aun siendo todavía necesario un consenso sobre qué forma de entrenamiento de fuerza es más adecuada para la mejora del rendimiento en corredores de alto nivel, la revisión de la literatura aporta suficientes evidencias que subrayan la importancia que el entrenamiento de fuerza tiene en las

system [5,44,68]. Specifically, strength training can increase the recruitment of fast fibers, the synchronization of motor units, the muscle power output or reduce the contact time of the stride [10,44]; adaptations that appear to be important to improve running performance [42,44,45,75]. In this sense, improvements in running economy, neuromuscular performance, and running performance have been observed after different strength training program with no changes in VO₂max [68 , 76]. However, given the limited number of investigations with high-level athletes, and the different kinds of the strength training programs used, more studies are needed to understand, first, how strength training can improve running performance and second, what is the best strength training stimuli for this population. However, although the optimum type of strength training for high-level distance runners still needs to be discussed, the literature review provides sufficient evidence to highlight the importance that strength training has on

carreras de media y larga distancia en deportistas de todos los niveles [11,12,14,41,67].

Por ello, siendo bien conocido que (a) la medición del rendimiento físico es imprescindible para programar las cargas de entrenamiento de los deportistas adecuadamente[17], y que (b) el entrenamiento de fuerza parece tener un papel importante en la preparación de los corredores de media y larga distancia[11,12,14], es fundamental evaluar adecuadamente la producción de fuerza de dichos deportistas con el fin de diseñar sus programas de entrenamiento de la mejor manera posible.

Evaluación de la producción de fuerza aplicada al mediofondo y fondo de alto nivel

El análisis de la evolución de la producción de fuerza permite planificar las cargas de entrenamiento, evaluar sus efectos sobre el rendimiento e incluso, como veremos más adelante, aporta información relevante sobre el grado de fatiga de los deportistas [32,52,56,59,77]. Existen multitud de pruebas tanto de campo como de laboratorio, para valorar la producción de fuerza en el deporte[59,78-80]. Las

middle and long-distance running performance on athletes of all levels [11,12,14,41,67].

Therefore, being well known that (a) the measurement of physical performance is essential to program adequate training loads [17], and (b) strength training seems to have an important role in the preparation of middle and long distance runners [11,12,14], it is essential to properly assess the force production of these athletes, so their strength training programs can be designed in the best way possible.

Evaluation of force production on high-level middle and long-distance runners

The analysis of the evolution of force production can help to program training loads, to evaluate its impact on performance and even to provide important information about the degree of fatigue of athletes [32,52,56,59,77]. There are many field and laboratory tests to assess force production in sport [59,78-80]. Laboratory

pruebas de laboratorio permiten una visión más interna de la capacidad de producir fuerza de la musculatura mediante el análisis, por ejemplo, de la velocidad de acortamiento de fibras musculares[81-84] (in vitro con fibras aisladas o in vivo mediante el uso de la llamada twitch interpolation technique), del rendimiento en test isocinéticos[85,86] o de los cambios en la arquitectura muscular mediante resonancia magnética nuclear [49,87]. Sin embargo, los test de campo son muchas veces una solución más adecuada por su especificidad con los ejercicios de entrenamiento y competición, así como por la facilidad de su aplicación en deportistas de élite, siendo probablemente los más utilizados los sprints cortos, el salto vertical o el rendimiento en ejercicios de fuerza como la sentadilla o el press de banca [57,61,88,89].

En primer lugar, las pruebas de sprint han sido ampliamente utilizadas en numerosas especialidades deportivas por su especificidad con el gesto de competición, su facilidad de administración y su alta fiabilidad [90-92]. Así, los sprints cortos (usualmente, de 10-50m) son muy comunes en las baterías de test de condición física tanto en deportes colectivos [90,93,94] como

tests provides a better insight into the strength capabilities of the musculature by analyzing, for example, the shortening speed of muscle fibers [81-84] (in vitro with isolated fibers or in vivo by using the twitch interpolation technique), the performance on isokinetic test [85,86] or changes in muscle architecture measured with magnetic nuclear resonance imaging [49,87]. However, field tests are often a more appropriate solution for their specificity with training and competition, as well as for their ease of use with elite athletes, being probably the most used the short sprints, the vertical jump tests or strength exercises such as squats or bench press [57,61,88,89].

First, sprint tests have been widely used in many sports disciplines for its specificity with the gesture of competition, ease of administration and high reliability [90-92]. So, short sprints (usually from 10-50m) are very common in fitness testing for both team [90,93,94] and

individuales[42,44]. En concreto, los test de sprint constituyen la valoración más específica (biomecánicamente hablando) de la producción de fuerza de los corredores [44,95]. De hecho, se han observado correlaciones elevadas y significativas, del orden de $r>0.70$, entre el tiempo en el sprint de 50 metros y el tiempo en recorrer 10.000m en corredores populares [95]. Este hecho, unido a la importancia que la producción de potencia anaeróbica parece tener sobre el rendimiento en las carreras de resistencia [45,96,97], justifica la utilización de los test de sprint cortos para la valoración de la producción de fuerza en los corredores de media y larga distancia.

En segundo lugar, las pruebas de salto vertical son ampliamente utilizadas por entrenadores, preparadores físicos e investigadores en ciencias del deporte para valorar la fuerza explosiva de los miembros inferiores de los deportistas [56,88]. De las múltiples variantes que se han descrito en la literatura, la más utilizada, por su validez, fiabilidad y especificidad, probablemente sea el salto vertical con contramovimiento (CMJ, por sus siglas en inglés: Counter Movement Jump)[88,98]. La facilidad de medición y el casi nulo grado de fatiga que genera el CMJ permite su valoración no

individual sports [42,44]. Specifically, the sprint test is the most specific assessment of the force production in runners (biomechanically speaking) [44,95]. In fact, high and significant correlations (about $r> 0.70$) between the 50m sprint and the 10.000m time trial in amateur runners have been observed [95]. This fact, coupled with the importance that anaerobic power output seems to have on distance running performance [45,96,97], justifies the use of short sprint tests for assessing force production on middle and long distance runners.

Second, vertical jump tests are widely used by coaches, trainers and researchers in sport science to assess athletes' lower limbs explosive strength [56,88]. Although many vertical jump tests have been described in the literature, probably the most used is the countermovement jump (CMJ) because of its validity, reliability and specificity (CMJ) [88,98]. The ease of measurement and the almost null fatigue that the CMJ produce allows its evaluation not

sólo en deportistas de alto nivel [99], sino también en niños[100] o ancianos [101], entre otros. Así, el salto vertical constituye una habilidad altamente específica para numerosas especialidades deportivas, por lo que su valoración es básica en deportes como el baloncesto, el voleibol o el fútbol [55,102-104]. Es más, el salto vertical está siendo utilizado también en corredores de alto nivel dado que, como se ha explicado con anterioridad, la potencia muscular de los miembros inferiores se considerada relevante en el rendimiento en especialidades de resistencia[42,46,68]. Por ejemplo, se han encontrado relaciones significativas (del orden de $r \approx 0.6-0.7$) entre la fuerza producida en el CMJ y el consumo de oxígeno en diversas fases de un test de carrera en corredores entrenados[46]. Por último, como veremos más adelante, se ha demostrado que el CMJ está estrechamente relacionado con el grado de fatiga metabólica y mecánica[32], por lo que su monitorización puede aportar información relevante en el proceso de entrenamiento. Por ejemplo, se ha mostrado que una carrera de maratón de alto nivel produce un decremento de aproximadamente un 16% en la capacidad de salto vertical [105].

En tercer lugar, la medición de la fuerza producida en los ejercicios de

only in high-level athletes [99] but also in children [100] or elderly [101], among others. Thus, the vertical jump is a highly specific skill for many sports specialties, so its valuation is essential in sports such as basketball, volleyball or soccer [55,102-104]. Moreover, the vertical jump is also being used in high-level runners since, as explained above, the muscular power of the lower limbs are considered relevant in endurances specialties [42,46,68]. For example, significant relationships were found (about $r \approx 0.6-0.7$) between the force produced in the CMJ and the oxygen consumption in various phases of a running test in trained runners [46]. Finally, as discussed below, it has been shown that the CMJ is closely related to the degree of metabolic and mechanical fatigue [32], so monitoring it can provide relevant information in the training process. For example, it has been shown that a high-level marathon competition produces a decrease of approximately 16% in vertical jumping performance [105].

Thirdly, the measurement of the force produced in the most common

entrenamiento más comunes como la sentadilla o el press de banca ha sido utilizada ampliamente para observar la mejora del rendimiento en dichos ejercicios[106-108]. En concreto, la evaluación de la Repetición Máxima (RM, la carga que sólo puede desplazarse una vez) es el centro de la valoración de la producción de fuerza desde hace décadas, y su utilización sigue siendo predominante no sólo en especialidades con grandes necesidades de fuerza como la halterofilia o el rugby [109,110], sino también en las carreras de mediodistancia y fondo [70,111]. De hecho, se han observado correlaciones elevadas entre la RM en sentadilla y la capacidad de sprint o salto vertical en diversos deportistas de alto nivel [89,112]. Sin embargo, a pesar de su popularidad, se han identificado una serie de inconvenientes que justifican su erradicación a favor de otras metodologías menos invasivas y más precisas, a saber [59,80]: (1) la ejecución de una RM conlleva una máxima preparación psicológica por parte del individuo dada la gran magnitud de la carga que debe movilizar, por lo que su medida tiende a estar subestimada; (2) la ejecución de una RM supone un esfuerzo muy intenso para el deportista que puede influir negativamente en su sesión de entrenamiento; (3) derivado de lo anterior,

training exercises such as the squat or the bench press has been widely used to observe the strength performance improvement [106-108]. Specifically, the evaluation of the repetition maximum (RM, the load that can be moved just once) has been the center of the measurement of strength capabilities for decades, and its use remains prevalent not only in specialties with high needs of strength such as weightlifting or rugby [109,110], but also in middle and long distance running [70,111]. In fact, high correlations were observed between squat RM and short sprints and vertical jumps in various high-level athletes [89,112]. However, despite its popularity, a number of drawbacks that justify its elimination in favor of other less invasive and more precise methodologies have been identified [59,80]: (1) performing a RM test involves maximum psychological preparation given the magnitude of the load that must be moved, so that its measure tends to be underestimated; (2) lifting the RM is a very intense effort for the athlete that can adversely affect his or her workout; (3) derived from the above,

la RM no puede medirse con mucha frecuencia, pues podría llevar al deportista a un estado de sobreentrenamiento; (4) la RM supone un riesgo de lesión innecesario, especialmente para aquellos deportistas que no están acostumbrados a movilizar cargas elevadas como los corredores de mediofondo y fondo.

Buscando una alternativa a esta metodología del uso de la RM para la valoración de la producción de fuerza, González-Badillo y Sánchez-Medina [59] llevaron a cabo un estudio en el cual midieron la velocidad media propulsiva en el ejercicio de press de banca en más de 150 expertos en fuerza. Utilizando cargas desde el 30% hasta el 100%RM, los autores comprobaron que cada uno de esos porcentajes de la RM tiene una misma velocidad media propulsiva asociada, independiente de los sujetos y de su estado de entrenamiento. De esta forma, midiendo la velocidad media propulsiva podemos conocer con exactitud el porcentaje de la RM que el ejercicio le supone al deportista sin necesidad de realizar nunca un test de RM. Estos hallazgos suponen una metodología menos invasiva y más precisa para conocer la intensidad de entrenamiento en los ejercicios de fuerza, y es especialmente útil con aquellos

the RM can not be measured very frequently, because it could produce too much fatigue; (4) the RM measurement represent an unnecessary risk of injury, especially for athletes who barely mobilize high loads as distance runners.

Looking for an alternative to this RM methodology for evaluation force production, González-Badillo and Sanchez-Medina [59] conducted a study that measured the mean propulsive velocity on the bench press in more than 150 experts in strength. Using loads from 30% to 100% RM, the authors found that each of these percentages has one specific mean propulsive velocity, independent of the subject and their training status. Thus, by measuring the mean propulsive velocity we can know the percentage of RM with which the athlete is training in a very accurate way without performing a RM test anymore. These findings imply a less invasive and more accurate methodology for monitoring training intensity on strength exercises, and it is especially useful to those

deportistas, como los corredores de media y larga distancia, que no están acostumbrados a movilizar cargas muy elevadas y que, por lo tanto, podrían correr riesgos innecesarios en la valoración tradicional de la RM.

En resumen, los sprints cortos, el salto vertical con contramovimiento y la medición de la velocidad de ejecución en ejercicios de fuerza, ya sea por su especificidad con el gesto de carrera, por su capacidad para detectar grados de fatiga o por su precisión de medición sin suponer un riesgo de lesión, constituyen una batería de test muy apropiada para valorar la fuerza de los corredores de alto nivel.

athletes, such as middle and long-distance runners, which are not used to mobilize very high loads and, therefore, may take unnecessary risks with the traditional assessment of the RM.

Summarizing, short sprints, countermovement jump and the measurement of movement velocity on strength exercises as the squat are very appropriate tests for the evaluation of force production on high-level distance runners because of its specificity, its ability to detect states of fatigue or its safe measurement.

Carga de entrenamiento

Training load



Principales indicadores de la carga de entrenamiento en mediofondo y fondo

Indicadores de carga externa: plan de entrenamiento

La cuantificación, evaluación y prescripción de la carga de entrenamiento es, probablemente, el proceso más importante en el incremento del rendimiento deportivo [1,4,17,113]. Sin embargo, aún no se ha alcanzado un

Main indicators of training load in middle and long-distance running

Indicators of external load: training plan

Quantifying, evaluating and prescribing training loads are probably the most important factors for increasing athletic performance [1,4,17,113] process. However, a consensus about which is the

consenso sobre cuál es el indicador más preciso de la carga de entrenamiento, pues sus efectos sobre el organismo varían en función del tipo de deportista y los problemas metodológicos e instrumentales en su medición son todavía muy grandes [17,19,114]. En su estudio, la carga de entrenamiento puede analizarse desde dos perspectivas: la externa y la interna[17,18].

La carga externa representa el valor objetivo de trabajo que el entrenador programa para el deportista. En el caso del mediofondo y el fondo, la variable de carga externa más extendida es el volumen de las sesiones semanales de carrera, esto es, el número de kilómetros recorridos por semana [24,37,40]. En cuanto a la carga interna, ésta hace referencia al valor individual que un determinado estímulo le ha supuesto a un deportista en concreto en función de sus características[17,18]. En las pruebas de carrera, por ejemplo, el umbral anaeróbico o la frecuencia cardíaca son dos indicadores de carga interna ampliamente utilizados[4,115,116]. De esta forma, un mismo valor de carga externa (por ejemplo, sesión de rodaje de 15 kilómetros), supondrá un estímulo interno diferente a cada uno de los atletas de un grupo de entrenamiento.

most accurate indicator of training load has not been established, since its physiological responses vary depending on the characteristics of the athletes and methodological problems on its measurement are still very large [17,19,114]. When studying it, training load can be analyzed from two perspectives: external and internal [17,18].

The external load is the objective amount of training that the coach programs for his or her athletes. For middle and long-distance runners, the most widely used external load indicator is the training volume, that is, the number of running km per week [24,37,40]. The internal load refers to the individual, physiological response that a given stimulus produce on the athlete [17,18]. In run tests, for instance, the anaerobic threshold or heart rate are two indicators widely used indicators of the internal load [4,115,116]. Thus, the same value of external load (eg running session of 15 km), could produce different internal responses to different athletes.

A pesar de que la carga externa no permite conocer el estímulo interno que el entrenamiento le supone al deportista, su facilidad de administración y control hace que su uso esté ampliamente extendido en centros de entrenamiento e investigación de todo el mundo; motivo por el cual la planificación de las cargas de entrenamiento de corredores de élite no podría entenderse sin la especificación de los kilómetros a correr en cada sesión [36,37,117]. De hecho, la cantidad total de kilómetros recorridos por semana es una referencia común para diferenciar corredores de distintas pruebas y niveles de rendimiento [40,118]. Por ejemplo, se considera que los corredores de mediofondo de alto nivel deben hacer como mínimo más de 50 kilómetros a la semana [12].

Sin embargo, el mero conocimiento de la cantidad de kilómetros que un corredor realiza por semana no aporta suficiente información sobre el estímulo del entrenamiento. Así, es necesario saber también cómo se han corrido esos kilómetros para entender mejor la carga externa que se le ha administrado al deportista. Para ello, se utilizan las zonas de entrenamiento [115,119]. Las zonas de entrenamiento consisten en 3-5 franjas o intervalos en los cuales se organizan las

Although the external load does not reveal the internal stimulus that the training suppose to the athlete, its ease of administration and control makes its widespread in research and training centers around the world; for example, training programs of elite runners could not be understood without specifying the running km of in each session [36,37,117]. In fact, the total number of running km per week is a common reference for differentiating runners of different specialities and levels [40,118]. For example, it is considered that high-level middle distance runners should run at least more than 50 km per week [12].

However, the mere knowledge of the number of km trained per week does not provide enough information about the training stimulus. Thus, it is necessary to know also how those km were trained to better understand the external load that has been administered to the athlete. To this end, training zones are used [115,119]. Training zones consist in 3-5 intervals in which running sessions

sesiones de carrera. Aunque dichas zonas suelen crearse tomando como referencia distintos porcentajes de la frecuencia cardíaca o el consumo máximo de oxígeno [24,37,115], se pueden diseñar también zonas de entrenamiento usando variables de carga externa como la velocidad media de cada sesión de entrenamiento [4,120].

No obstante, aunque el control de la carga externa en volumen y zonas de entrenamiento tiene una utilidad práctica incuestionable tanto para el entrenador como para los atletas, son necesarios indicadores de la carga interna de los entrenamientos para poder obtener una idea más precisa sobre los efectos internos que producen los estímulos que se programan, pues su conocimiento puede ayudar a prevenir los estados de overreaching o sobreentrenamiento [17,121]. En la siguiente sección hablaremos de algunos de los más utilizados.

Indicadores de carga interna: marcadores fisiológicos y esfuerzo percibido

En el entrenamiento de las pruebas de mediofondo y fondo de alto nivel, los atletas someten a su organismo a unos

are classified. Although these zones are typically created with reference to different percentages of the maximum heart rate or oxygen consumption [24,37,115], they can also be designed using external variables as the average pace of each training session [4,120].

However, although monitoring training volume and zones has an unquestionable practical value to both the coach and athletes, the use of indicators of the internal training load is needed in order to get a more precise idea about the internal effects that programmed stimulus produces, because its knowledge can help to prevent overreaching or overtraining states [17,121]. The following section will discuss some of the most used internal load indicators.

Internal load indicators: rate of perceived exertion and physiological markers

High-level middle and long-distance runners conduct very intense

estímulos de tal intensidad que, mal administrados, pueden producir fácilmente descensos en el rendimiento o estados de overreaching [2,16,122]. De esta forma, es fundamental conocer el grado de esfuerzo que los entrenamientos les suponen a los deportistas para organizar las cargas de trabajo de los distintos ciclos de la temporada de manera racional y con menor riesgo de overreaching o sobreentrenamiento.

Para tal fin, actualmente lo más preciso desde el punto de vista fisiológico sería, probablemente, medir los gases inspirados y expirados por el deportista durante el entrenamiento para conocer con precisión a qué porcentaje del consumo máximo de oxígeno, umbrales ventilatorios o anaeróbico han trabajado[123-125]. Sin embargo, aunque técnicamente sería posible realizar dicha medición en el campo gracias a los analizadores de gases portátiles [125], la gran incomodidad que les supondría a los atletas llevar una mochila y una máscara en cada sesión de entrenamiento, así como su elevado coste, hace que su utilización sea prácticamente inviable en el día a día. Supliendo este gran inconveniente práctico, se han descrito relaciones significativas entre el consumo máximo de oxígeno o el umbral

training sessions in a daily bases, and a bad administration of these training loads, with an inappropriate recovery, can easily produce declines in performance or states of overreaching [2,16,122]. Thus, it is essential to know the level of fatigue that the training sessions produce on the athletes, so training loads can be organized during the different preparation periods to avoid the risk of overreaching or overtraining.

To this end, currently the most accurate approach (from a physiological point of view) would be the measurement of inspired and expired gases during training to know precisely at which percentage of maximal oxygen uptake, ventilatory and anaerobic thresholds athlete training is training [123-125]. However, although technically it would be possible to make this measurement in the field thanks to the portable gas analyzers [125], the great discomfort that carrying a backpack and a mask in each training session would produce to the athletes, as well as its high cost makes it virtually impossible to use in a daily basis right in the track. Significant relationships between maximal oxygen uptake or the anaerobic

anaeróbico con la frecuencia cardíaca de los deportistas, de tal forma que los entrenamientos podrían prescribirse en distintas zonas de intensidad en función de los valores de frecuencia cardíaca [6,20,21]. No obstante, se sabe que la frecuencia cardíaca no aumenta de manera lineal con el consumo de oxígeno en zonas de intensidad muy elevadas, pudiéndose producir un “plateau” o meseta mientras el VO₂ sigue incrementándose hasta llegar a su máximo valor [6,126]. De hecho, durante las series de sprints cortos con poca recuperación, el consumo de oxígeno puede elevarse súbitamente para luego disminuir notablemente entre cada repetición, mientras que la frecuencia cardíaca permanecería elevada durante todo el entrenamiento sin apenas dar tiempo a su disminución durante la recuperación [127]. De esta forma, los atletas de alto nivel, acostumbrados a trabajar en zonas cercanas y superiores al VO₂Máx, y con un gran número de sesiones de entrenamiento interválico, no obtendrían valoraciones precisas sobre la intensidad del entrenamiento observando sus niveles de frecuencia cardíaca [6]. Además, desde la experiencia práctica en la pista de entrenamiento, es muy frecuente que los atletas de alto nivel entrenen diariamente sin monitor de frecuencia cardíaca, pues la

threshold and the heart rate of the athletes have been described, so that training may be prescribed in different intensity zones based on the values of heart rate [6,20,21]. However, it is known that heart rate does not increase linearly with oxygen consumption in areas of very high intensity, being able to produce a plateau while the VO₂Max continues to rise until it reaches its maximum value [6,126]. In fact, in interval trainings consisting on short sprints with short recovery, oxygen consumption can rise suddenly and then decrease significantly between each repetition, while heart rate will remain high throughout the training without enough time to return to lower levels during recovery [127]. Thus, high-level athletes, accustomed to train with interval stimulus near an above the VO₂max on a regular basis, would not obtain accurate assessments of their training intensity levels observing exclusively their heart rate responses [6]. Also, experience tell us that high-level athletes don't use to train with heart rate monitors on a daily basis, since

banda del pecho les resulta incómoda y prefieren entrenar por tiempo y por sensaciones. Por ello, muchos atletas pueden rechazar la utilización sistemática de monitores de frecuencia cardíaca si se desea monitorizar el entrenamiento cada día durante un periodo de tiempo largo (por ejemplo, una temporada).

En este sentido, la evaluación de la percepción subjetiva del esfuerzo (RPE, según su transcripción inglesa rate of perceived exertion) se ha propuesto como una alternativa práctica, no invasiva, gratuita y fiable para evaluar la intensidad que el estímulo de entrenamiento supone a los deportistas [29,128-131]. La evaluación del RPE consiste en preguntar al deportista cómo de intensa ha sido para él una determinada actividad (por ejemplo, una repetición de 400 metros) o el conjunto de un entrenamiento en una escala de 0 a 10 conocida como la escala de Borg-10 [34,132,133]. El estudio del RPE ha sido muy utilizado en la literatura en diversas especialidades deportivas incluidas las carreras de media y larga distancia [4,113,118,128,134]. Por ejemplo, se han observado correlaciones muy altas ($r=0.96$) entre los niveles de RPE y de lactato tomados cada 10 minutos en

they tend to find the chest band pretty uncomfortable, and prefer to train according to their running paces and perceived exertions. Therefore, many athletes may reject the systematic use of heart rate monitors for monitoring their training sessions for a long period of time (e.g., a season).

In this regard, the evaluation of the rate of perceived exertion (RPE) has been proposed as a practical, non-invasive, reliable and easy-to-use for monitoring the internal load [29,128-131]. The measurement of the RPE consist on asking the athlete how intense was a specific activity (e.g., a repetition of 400 meters) or a whole workout for them, on a scale of 0 to 10 [34,132,133]. The study of RPE has been widely used in the literature in various sports, including middle and long-distance running [4,113,118,128,134]. For example, there have been observed very high correlations ($r = 0.96$) between the levels of lactate and RPE taken every 10 minutes

karatecas de alto nivel durante un entrenamiento [131] e, incluso, se ha demostrado que el RPE puede ayudar a predecir con precisión el umbral de lactato [132]. En concreto, el RPE por sesión (session-RPE en inglés), una variante del RPE que engloba el grado de esfuerzo que una sesión entera de entrenamiento ha supuesto al deportista, ha sido utilizada en múltiples investigaciones como principal indicador de la carga de entrenamiento [29,30,135-137].

Por ejemplo, Moreira et al. [138] utilizaron el session-RPE como único indicador de la carga de entrenamiento en su estudio de 4 semanas con jugadores de fútbol sala profesionales, en el que identificaron una relación positiva y significativa ($r=0.75$, $p<0.05$) entre la carga de entrenamiento semanal y la infección del tracto respiratorio superior. Del mismo modo, el session-RPE se ha utilizado satisfactoriamente para monitorizar el grado de fatiga generado por diferentes tipos de entrenamiento de fuerza [29]. De esta forma, el session-RPE constituye un indicador ampliamente respaldado por la comunidad científica, significativamente relacionado con otros indicadores de la carga interna de entrenamiento como el lactato en sangre y de fácil aplicación

on high-level karateka during training [131] and even it has been shown that RPE can help accurately predict the lactate threshold [132]. Specifically, the RPE per session (session-RPE), a variant of the RPE that represents the degree of effort that a whole training session has produced to the athlete has been used in multiple investigations as a leading indicator of training load [29,30,135-137].

For example, Moreira et al. [138] used the session-RPE as the sole indicator of training load in their 4-week study with professional futsal players, in which they identified a significant positive relationship ($r = 0.75$, $p < 0.05$) between the weekly training load and upper-respiratory tract infection infection. Similarly, the session-RPE has been successfully used to monitor the degree of fatigue generated by different types of strength training [29]. Thus, the session-RPE is a widely used indicator on the scientific community, because of its ease and non-invasive administration and its significant relations with to other indicators of internal training load as blood lactate.

práctica en la pista de una manera no invasiva.

En resumen, la utilización del volumen y las zonas de entrenamiento como indicadores de carga externa, y del session-RPE como indicador de carga interna parece una propuesta razonable, no invasiva y práctica de valorar la carga de entrenamiento de los corredores de media y larga distancia de alto nivel.

Summarizing, the use of training volume and training zones as indicators of external load, and session-RPE as an indicator of internal load seems a reasonable, non-invasive and practice approach for assessing the training load of high-level middle and long-distance runners.

La fatiga

Fatigue



Qué es la fatiga

Aunque existen multitud de variables fisiológicas, psicológicas y ambientales que pueden influir en la aparición de la fatiga [139-141], y sin saberse todavía cuáles son las causas exactas de su aparición [139,142,143], en la literatura está muy aceptado que la fatiga, en última instancia, resulta en una disminución relevante en la capacidad de producir fuerza [143-145].

Dependiendo de la

What is fatigue

Although there are many physiological, psychological and environmental variables that can influence the onset of fatigue [139-141], and taking into account that the exact causes of its appearance are not well known yet [139,142,143], in the literature it is widely accepted that fatigue is a significant decrease in force production [143-145]. Depending on the

duración de la disminución del rendimiento físico, la fatiga puede ser aguda o crónica [146]. Por un lado, la fatiga aguda conlleva un decremento momentáneo del rendimiento, consecuencia del entrenamiento, que generalmente vuelve a sus valores iniciales al cabo de unas horas [146,147] y, aunque actualmente se está discutiendo la necesidad de generar un cierto grado de fatiga para mejorar el rendimiento [148], está ampliamente extendida la idea de que ciertos niveles de fatiga aguda son deseables para producir el efecto de supercompensación[121,149]. Por otro lado, la fatiga crónica constituye un estado de disminución del rendimiento prolongado en el tiempo y, a su vez, se subdivide en tres estados diferenciados: overreaching funcional, overreaching no funcional y sobreentrenamiento [121,146]. El overreaching funcional es un tipo de fatiga en la cual se produce un descenso del rendimiento durante unos pocos días o semanas que luego tiende a supercompensarse, es decir, a aumentar sus valores previos, mientras que el overreaching no funcional implica un descenso del rendimiento durante hasta un mes que luego vuelve a los niveles previos[121,146]. Por último, el estado de sobreentrenamiento es el más severo de todos los tipos de fatiga crónica e implica un descenso prolongado (> de 1 mes) del

duration of the physical performance impairment, fatigue may be acute or chronic [146]. On one hand, acute fatigue involves a momentary decrease of performance due to the training, which usually returns to its baseline values within a few hours [146,147]. Although the need to produce fatigue to improve performance is currently being discussed [148], it is widely accepted that certain levels of acute fatigue are desirable to produce the effect of super-compensation [121,149]. On the other hand, chronic fatigue is a prolonged state of decreased performance over time and, is divided into three different states: functional overreaching, nonfunctional overreaching and overtraining [121,146]. The functional overreaching is a type of fatigue in which performance is decreased for a few days or weeks, and then it super-compensate, i.e., it exceeds its previous values, while the non-functional overreaching involves a decrease in performance during up to a month followed by a return to its baseline values without super-compensation [121,146]. Finally, the state of overtraining is the most severe of all types of chronic fatigue and it involves a prolonged decline (> 1 month) on

rendimiento sin que se retorne a los niveles previos [150,151].

Una vez realizada esta breve descripción sobre los dos principales tipos de fatiga descritos en la literatura, pasaremos a enumerar algunos de los indicadores metabólicos, hormonales y mecánicos más utilizados para la monitorización del grado de fatiga de los deportistas.

Principales indicadores de la fatiga

Variables metabólicas: lactato sanguíneo

A pesar de que el lactato sanguíneo no ha sido medido en la presente Tesis Doctoral, su gran protagonismo en las valoraciones del grado de fatiga en la fisiología del ejercicio desde hace décadas [132,152-154], así como su relación con otros indicadores menos invasivos del esfuerzo como el RPE o el CMJ [32,128,131] le hacen merecer una breve mención en este marco conceptual. Este metabolito, resultado de la producción de energía mediante la glucólisis anaeróbica [96] está estrechamente relacionado con el incremento del esfuerzo durante el ejercicio, consiguiéndose la mayor

performance without return to its previous levels [150,151].

After this brief description of the two main types of fatigue reported in the literature, we will list some of the most commonly used metabolic, hormonal and mechanical markers of fatigued to monitor athlete's training process.

Main indicators of fatigue

Metabolic variables: blood lactate

Although blood lactate was not measured in this PhD research, it deserve a brief mention because of its leading role in the assessments of the degree of fatigue in exercise physiology for decades [132,152-154] as well as for its strong relationships to other less invasive indicators of effort or performance like the RPE or CMJ [32,128,131]. This metabolite, resulting from energy production through anaerobic glycolysis [96] is closely related to the increase in effort during exercise, with higher

producción de lactato con aquellos ejercicios que solicitan la activación de la glucólisis anaeróbica en mayor medida en un esfuerzo máximo de 40-60 segundos, como pueden ser las carreras de velocidad de 400 metros [96,153,154].

En un test en tapiz rodante en el que se aumenta la velocidad progresivamente hasta el máximo que el sujeto puede tolerar, los niveles de lactato se incrementan según la velocidad de carrera va siendo mayor y, a partir de un punto denominado umbral de lactato [8], la producción de dicho metabolito crece exponencialmente y el ejercicio sólo puede ser mantenido unos pocos minutos. De hecho, existen relaciones estrechas entre el aumento de la producción de lactato y el aumento del consumo de oxígeno, la frecuencia cardíaca o el RPE [8,22,155]. Además, para la medición del lactato en sangre, sólo es necesaria una pequeña muestra de sangre capilar, generalmente tomada del dedo o del lóbulo de la oreja [8]. Por estos motivos, así como por la facilidad de su medición en situaciones de campo en comparación con otras variables fisiológicas, las pruebas de lactato están ampliamente extendidas en la valoración del grado de fatiga de los deportistas ante un estímulo determinado [57,115,134,156].

lactate production with those exercises that request the most the anaerobic glycolysis system, such as 400m maximal sprints [96,153,154].

In a test on a treadmill where the speed is increased gradually to the maximum that the subject can tolerate, lactate levels are increased with running speed, and from a point called the lactate threshold [8], the production of this metabolite increases exponentially and exercise can be maintained only a few minutes. In fact, there are close relationships between increased lactate production and increased oxygen consumption, heart rate or RPE [8,22,155]. The measurement of blood lactate only needs a small sample of capillary blood, usually taken from the finger or earlobe [8]. For these reasons, as well as for the ease of its measurement in field situations compared to other physiological variables, lactate tests are widespread for the assessment of the fatigue produced by a particular training stimuli [57,115,134,156].

Sin embargo, la valoración del lactato en sangre tiene dos potenciales problemas metodológicos. En primer lugar, desde hace unos años se está cuestionando la validez del lactato para medir el grado de fatiga, pues diversas evidencias han demostrado que dicho metabolito no es uno de los causantes de la fatiga muscular sino que, de hecho, su aparición podría beneficiar la capacidad de producir fuerza [144,157,158]. En este sentido, a pesar de que el lactato aumenta exponencialmente con el incremento de la intensidad del ejercicio, su presencia se debería a un incremento de la utilización de las fibras de contracción rápida, de mayor capacidad glucolítica [144,157,158]. Por ello, se ha propuesto que otros indicadores, como los niveles de pH muscular o amonio en sangre podrían ser más apropiados para evaluar el grado de fatiga de los deportistas [32,144,159]. En segundo lugar, las pruebas de lactato conllevan diversas muestras de sangre capilar que, de realizarse continuamente (por ejemplo, una vez a la semana durante una temporada) podrían suponer un fuerte rechazo por parte de los deportistas.

Estos factores justifican la utilización de otros métodos no invasivos para valorar el grado de fatiga de los deportistas sin necesidad de tomar muestras de sangre.

However, the assessment of blood lactate has two potential methodological problems. First, in recent years the validity of the lactate for measuring the degree of fatigue is being questioned, because several evidences have shown that this metabolite is not one of the causes of muscle fatigue but, in fact, his appearance could benefit the ability to produce force [144,157,158]. Thus, even though lactate increases exponentially with the increase in exercise intensity, its presence could be due to an increase in the use of fast-twitch fibers, which has more glycolytic capacity [144,157,158]. Therefore, it has been proposed that other indicators, such as levels of muscle pH or blood ammonia may be more appropriate to assess the degree of fatigue of athletes [32,144,159]. Second, lactate tests needs several samples of capillary blood, so a systematic measurement (for example, once a week throughout a season) could be very invasive for the athletes.

These drawbacks justify the use of other non-invasive methods to assess the degree of fatigue of athletes in a regular basis without taking blood samples.

En concreto, y como veremos a continuación, durante los últimos años han proliferado los estudios que analizan diversas hormonas relacionadas con la fatiga mediante sencillas muestras de saliva.

Variables hormonales: Cortisol en saliva

Las hormonas son un tipo de proteínas que, actuando como mensajeras, regulan diversas funciones del organismo incidiendo sobre determinadas células receptoras [3,50]. Por ejemplo, la hormona de crecimiento es un tipo de hormona peptídica que estimula la regeneración celular y el crecimiento[3]. En el deporte, tradicionalmente, las hormonas que más presencia han tenido en la evaluación de los deportistas son la testosterona y el cortisol por su capacidad para indicar estados anabólicos o catabólicos [160-162]. Ambas son secretadas por la glándula suprarrenal, aunque, en el caso de la testosterona, los principales secretores son los testículos (en los hombres) y los ovarios (en las mujeres) [3,163]. Mientras que la testosterona es una hormona anabólica, es decir, relacionada con procesos de construcción de componentes celulares,

el

Specifically, as discussed below, in the recent years a proliferation of studies examining various hormones related to states of fatigue using saliva samples has been observed.

Hormonal Variables: Salivary Cortisol

Hormones are a type of proteins that act as messengers, regulating many body functions incising on certain target cells [3,50]. For example, growth hormone is a type of peptide hormone that stimulates cell renewal and growth [3]. In sports the hormones that have had more presence in the evaluation of athletes was testosterone and cortisol because of its ability to indicate anabolic or catabolic states [160-162]. Both are secreted by the adrenal gland, although in the case of testosterone, the main secretory are the testicles (in men) and ovaries (in women) [3,163]. While testosterone is an anabolic hormone, that is related to processes of construction of cellular components,

cortisol tiene funciones catabólicas, o de degradación [3]. Por ello, niveles de testosterona normales o ligeramente elevados indican un estado de recuperación deseado por los deportistas, mientras que niveles altos de cortisol se suelen relacionar con estrés y fatiga [26,164,165].

Aunque tradicionalmente dichas hormonas se han medido en sangre [166,167] existen técnicas fiables para medir la concentración de cortisol y testosterona en saliva [27,168]. Por ello, dada la enorme utilidad práctica que implica poder evaluar dichas hormonas con una sencilla muestra de saliva (que suele recogerse mascando un algodón o frotándose un bastoncillo por la boca), su uso se ha popularizado en estudios con deportistas de alto nivel a los que sería muy complicado extraer muestras de sangre en situaciones de campo y/o de competición [33,169-171]. Por ejemplo, Cormack et al. [77] midieron los niveles de cortisol libre en saliva durante 22 semanas consecutivas en jugadores profesionales de fútbol australiano para analizar su evolución durante el periodo competitivo y su relación con la carga de entrenamiento, concluyendo que aquellos deportistas con mayores niveles de cortisol al inicio de temporada podrían ver reducido en mayor

cortisol has catabolic or degradation functions [3]. Therefore, normal or slightly elevated testosterone levels may indicate a desired recovery state, while high levels of cortisol are usually related to stress and fatigue [26,164,165].

Although traditionally these hormones have been measured in blood [166,167] it also exists reliable techniques for measuring cortisol and testosterone in saliva [27,168]. Therefore, given the enormous practical utility which involves evaluating these hormones with a simple saliva sample (typically collected by chewing a cotton or rubbing the mouth with a cotton-swab), its use has become popular in studies with high-level athletes, where collecting blood samples in field and/or competition situations is difficult [33,169-171]. For example, Cormack et al. [77] measured the levels of free cortisol in saliva for 22 consecutive weeks in professional Australian football players to analyze its evolution during the competitive period and its relationship with training load, concluding that those athletes with higher levels of cortisol at the beginning of the season could see reduced further

medida su rendimiento neuromuscular a lo largo del año. Del mismo modo, otros autores han estudiado la relación entre el cortisol y la testosterona en saliva y diversos test de fuerza [169,170,172] para averiguar si dichas hormonas pueden ser utilizadas como predictoras del rendimiento físico en ejercicios de fuerza. Estas interesantes aproximaciones metodológicas, que estudian en profundidad las consecuencias de toda una temporada de competición en los niveles hormonales de atletas profesionales, difícilmente podrían llevarse a cabo mediante muestras de sangre, pues su extracción sistemática, una vez a la semana durante un periodo prolongado sería poco aceptado por los deportistas.

De esta forma, el análisis del cortisol libre en saliva, por su relación con estados de estrés y catabolismo, así como por su medición no invasiva, está siendo cada vez más utilizado para estudiar los efectos del entrenamiento en deportistas de alto nivel.

their neuromuscular performance throughout the year. Similarly, other authors have studied the relationship between cortisol and testosterone in saliva with various strength test [169,170,172] to determine whether these hormones can be used as predictors of physical performance in strength training. These interesting methodological approaches, studying the effects of a whole season of competition in the hormonal responses of professional athletes, could hardly be done using blood samples, because a weekly collection for an extended period of time would be unacceptable by athletes.

Thus, the analysis of salivary-free cortisol is increasingly being used to study the effects of training on high-level athletes because of its association with stress and catabolic states, as well as for its non-invasive measurement.

El salto vertical como indicador del grado de fatiga

Como ya se ha comentado, la fatiga resulta, en última instancia, en una pérdida de la capacidad de producir fuerza en el gesto deportivo [143], y esto es aplicable no sólo a las especialidades de fuerza, sino también a las carreras de mediofondo y fondo. Por ejemplo, supongamos el caso de un mediofondista que decide retirarse de una prueba de 1.500 metros porque no puede continuar corriendo. Las causas de esa fatiga pueden deberse a motivos fisiológicos (depleción notable de las reservas de glucógeno, aumento de la acidez muscular) o psicológicos (incapacidad para aguantar el sufrimiento propio de la prueba) entre otros factores, pero, en definitiva, que el deportista se pare implica que no es capaz de aplicar la suficiente fuerza con la musculatura de sus miembros inferiores para impulsar su cuerpo a la velocidad que requiere la carrera.

De esta forma, sabiendo que la fatiga consiste en una disminución del rendimiento físico [142,143,145], resulta lógico pensar que dicho decremento pueda ser utilizado como un indicador válido del grado de fatiga. Sin embargo, desde un punto de vista metodológico,

The vertical jump as an indicator of fatigue

As mentioned above, fatigue is, ultimately, a loss of the ability to produce force in a specific exercise or movement [143], and this applies not only to strength sports, but also to middle and long-distance running. For example, lets guess the case of a middle-distance runner who decides to withdraw from a 1500m because he can not continue running. The causes of his fatigue may be due to physiological reasons (remarkable depletion of glycogen stores, increased muscle acidosis) or psychological (inability to endure with the effort of the race) among other factors, but ultimately it implies that the athlete is not able to apply enough force with the muscles of his legs to move his body at the required speed.

Thus, knowing that fatigue results in a decrease in physical performance [142,143,145], it is logical to think that this decrease can be used as a valid indicator of fatigue. However, from a methodological point of view,

sólo podrían ser válidos aquellos test que, por sí mismos, no produjeran un grado de fatiga todavía mayor en el deportista, lo cual enmascararía su medición, y que pudieran aplicarse sencillamente de manera sistemática. Por ejemplo, no sería adecuado valorar el grado de fatiga utilizando el test de Repetición Máxima, pues su propia realización supondría un grado de fatiga muy elevado para los deportistas y, además, no podría realizarse con frecuencia por su riesgo de lesiones y sobreentrenamiento [57,59,60]. En este sentido, desde hace algunos años se está utilizando el salto vertical con contramovimiento (en adelante, CMJ) como indicador del grado de fatiga por la estrecha relación que guarda con otras variables metabólicas y mecánicas relacionadas con el esfuerzo [32,102,140,173,174]. Por ejemplo, se ha demostrado que el decremento en la altura alcanzada en el CMJ después de diversas series en sentadilla está estrechamente ($r>0.90$) relacionado con la acumulación de lactato y amonio en sangre, así como con la pérdida de velocidad de ejecución en dicho ejercicio [32]. Del mismo modo, se ha probado que la pérdida en la altura en el CMJ está significativamente relacionada ($r=-0.77$, $p<0.05$) con el decremento del rendimiento en una serie de sprints

it could only be valid those tests that, by themselves, do not produce a greater degree of fatigue and could be applied in a simple, systematic way. For example, it would be inappropriate to assess the degree of fatigue using the RM test, because its own measurement could produce a very high degree of fatigue on the athletes and it could not be performed frequently for its risk of injury or overreaching [57,59,60]. In this sense, the use of the countermovement jump (CMJ) as an indicator of fatigue has been proposed in the recent years because of its close relationship with other variables related to metabolic and mechanical fatigue [32,102,140,173,174]. For example, it has been shown that the decrease in the CMJ height after several series on the squat exercise is closely ($r>0.90$) related to the levels of blood lactate and ammonium, as well as with the loss of velocity in that exercise [32]. Similarly, it has been proved that the CMJ height loss is significantly related ($r = -0.77$, $p <0.05$) with the performance decrement during a number of maximal

máximos de 40-80 metros [173]. A pesar de que en la literatura la evaluación de la pérdida de altura en el CMJ se ha utilizado fundamentalmente con deportistas de especialidades relacionadas con la fuerza explosiva como el baloncesto [77,102,175], también se ha usado en deportistas de resistencia. En concreto, se han observado decrementos significativos de hasta un 16% en la altura en el CMJ después de una maratón [105,176].

La principal ventaja de la aplicación del CMJ como indicador de fatiga frente a otras variables relacionadas con la capacidad de aplicar fuerza como podría ser el sprint de 20 metros o la RM reside en su facilidad de administración y en su inocuidad. Mientras que los sprints cortos y el test de RM necesitan de un calentamiento previo para evitar posibles lesiones, el CMJ puede realizarse con seguridad para el deportista incluso antes de haber calentado. Además, el CMJ puede medirse a diario sin que ello afecte al estado de entrenamiento de los deportistas, cuando los sprints cortos, y especialmente la RM, no pueden medirse con frecuencia por el elevado esfuerzo que suponen y el efecto sobre el rendimiento que ello supondría [57,59,62].

40-80m sprints [173]. Although the evaluation of the CMJ height has been investigated primarily with explosive-strength athletes such as basketball players [77,102,175], it has also been used with endurance athletes. Specifically, significant decreases up to 16% in the CMJ height after a marathon race was observed [105,176].

The main advantage of the application of CMJ as an indicator of fatigue, compared to other variables related to force production as the 20m sprint or the RM lies in its ease of administration and safety. While the short sprints and RM tests requires a complete warm-up to avoid possible injury, the CMJ can be performed safely for athletes even before they have warmed up in just a few seconds. In addition, the CMJ can be measured daily without affecting the training process of the athletes, while short sprints, and specially the RM can not be measured that frequently because of the high effort required to its completion and the negative effects that it could produce on performance [57,59,62].

De esta forma, la evaluación del salto vertical como indicador del grado de fatiga de los deportistas ante diversos esfuerzos, ya sean de fuerza o de resistencia, está ganando presencia en la literatura científica por su facilidad de medición, su inocuidad y su relación con otras variables relacionadas con el esfuerzo físico.

Thus, the assessment of vertical jump as an indicator of fatigue for both strength and endurance athletes is gaining presence in the scientific literature for its ease of measurement, its safety and its relationship with other variables related to physical effort.

2

Parte empírica *Empirical Work*

**“A person who never made
a mistake never tried
anything new”**

– Albert Einstein



Instrumental y Métodos

Materials & Methods



Objetivos y aproximación metodológica

Objetivo general de la Tesis Doctoral

Conocer las relaciones existentes entre la capacidad de producir fuerza, la carga de entrenamiento, el grado de fatiga y el rendimiento competitivo en un grupo de corredores de media y larga distancia de alto nivel.

Purposes and methodological approach

Main purpose of this PhD Thesis

To know the relationship between the ability to produce force, the training load, the degree of fatigue and competitive performance in a group of high-level middle and long distance runners.

Objetivos específicos de la Tesis Doctoral

1. Analizar la relación entre la carga de entrenamiento, los niveles de salto vertical, cortisol libre en saliva y el rendimiento en competición (marca en cada una de las competiciones oficiales reconocidas por la Real Federación Española de Atletismo) durante toda una temporada en corredores de mediofondo y fondo de alto nivel. (Objetivo 1 abordado en el Artículo 1 de la presente Tesis Doctoral).
2. Estudiar la evolución de la fuerza de los miembros inferiores durante toda la temporada y después del descanso de final de temporada en corredores de mediofondo y fondo de alto nivel, así como su relación con los niveles medios de carga de entrenamiento y cortisol libre en saliva. (Objetivo 2 abordado en el Artículo 2 de la presente Tesis Doctoral).
3. Analizar los efectos de la competición más importante de la temporada en el salto vertical, los niveles de cortisol libre en saliva y el esfuerzo percibido, así como la relación entre dichas variables, en corredores de mediofondo y fondo de alto nivel. (Objetivo 3 abordado en el Artículo 3 de la presente Tesis Doctoral).

Specific purposes of this PhD Thesis

- 1. To analyze the relationships between training load, countermovement jump height, salivary-free cortisol and competition performance (i.e., records on every single competition recognized by the Royal Spanish Athletics Federation) during a whole season in high-level middle and long-distance runners. (Purpose 1, addressed in the Paper #1 of the present PhD Thesis).*
- 2. To study the time-course of the lower limbs force production during the season and after the off-season break in high-level middle and long-distance runners, and to analyze its relationship with training load and salivary-free cortisol levels. (Purpose 2, addressed in the Paper #2 of the present PhD Thesis).*
- 3. To analyze the effects of the most important competition of the season in the vertical jump, salivary-free cortisol and perceived exertion levels, and to study the relationship between these variables, in high-level middle and long-distance runners. (Purpose 3, addressed in the Paper #3 of the present PhD Thesis).*

Aproximación metodológica

En la Tabla 1 se muestran las principales características metodológicas de la Parte Empírica de la presente Tesis Doctoral, detallando, para cada artículo, el diseño del estudio, las características de los participantes, las variables medidas y los análisis estadísticos utilizados. Para una descripción detallada de los aspectos metodológicos de cada artículo, véase la sección Methods de los mismos.

Methodological approach

The main methodological characteristics of the experimental work of this PhD Thesis are shown on Table 1, detailing, for each item, study design, participants' characteristics, measured variables and statistical analyses used are shown. For a detailed description of the methodological aspects of each paper, see its Methods section.

Reclutamiento de los participantes

Los participantes de la presente Tesis Doctoral son 15 corredores de mediofondo y fondo de alto nivel (12 hombres, 3 mujeres, marca 1500m: 3:38-3:58min –hombres–; 4:12-4:23min –mujeres–, marca 10000m : 29min24s-31min31s –hombres–; 33min45s-35min56s –mujeres–) pertenecientes a un mismo grupo de entrenamiento del Centro de Alto Rendimiento de Madrid (Madrid, España). Entre ellos, se encuentran múltiples medallistas nacionales e internacionales desde categoría promesa a senior. Para el Artículo 3, se estudiaron 10 de los 15 sujetos iniciales: aquellos que llegaron a la final del Campeonato de España Absoluto.

Recruitment of Participants

Participants in the present PhD research are 15 high-level middle and long-distance runners (12 men, 3 women, personal bests in 1500m 3:38-3:58min -men-, 4:12-4:23min -women-, personal bests in urban 10000m : 29 min 24 s -31 min 31 s - men -; 33min45s-35min56s -women-) training in the same group at the High Performance Center of Madrid (Madrid, Spain). They have many national and international medals, from U-23 to senior category.

TABLA 1. Principales características metodológicas de los Artículos de la presente Tesis Doctoral

	Artículo 1	Artículo 2	Artículo 3
Diseño	Estudio longitudinal de correlación y comparación de medias (39 semanas, de Octubre a Julio)	Estudio longitudinal de correlación y comparación de medias (47 semanas, de Octubre a Septiembre)	Estudio descriptivo, de correlación y de comparación de medias con línea base de 4 semanas
Participantes	15 corredores de mediofondo y fondo de alto nivel (12 hombres, 3 mujeres) <i>Edad:</i> 26.3 ± 5.1 años <i>IMC:</i> $19.7 \pm 1.1 \text{ kg/m}^2$ <i>T1500:</i> 3:38-3:58min (hombres); 4:12-4:23min (mujeres) <i>T10000:</i> 29min24s-31min31s (hombres); 33min45s-35min56s (mujeres)	15 corredores de mediofondo y fondo de alto nivel (12 hombres, 3 mujeres) <i>Edad:</i> 26.3 ± 5.1 años <i>IMC:</i> $19.7 \pm 1.1 \text{ kg/m}^2$ <i>T1500:</i> 3:38-3:58min (hombres); 4:12-4:23min (mujeres) <i>T10000:</i> 29min24s-31min31s (hombres); 33min45s-35min56s (mujeres)	10 corredores de mediofondo y fondo de alto nivel (7 hombres, 3 mujeres) <i>Edad:</i> 27.6 ± 5.1 años <i>IMC:</i> $19.6 \pm 1.3 \text{ kg/m}^2$ <i>T1500:</i> 3:38-3:47min (hombres); 4:12-4:23min (mujeres) <i>T10000:</i> 29min24s-31min31s (hombres); 33min45s-35min56s (mujeres)
Variables medidas	Carga de entrenamiento ^a : diariamente Cortisol libre en saliva y CMJ: una vez a la semana Rendimiento (marca) en cada una de las competiciones oficiales reconocidas en la RFEA	Sprint de 50m y producción de fuerza en media sentadilla ^b : 5 veces a lo largo del periodo de estudio Carga de entrenamiento ^a : diariamente Cortisol libre en saliva: una vez a la semana	CMJ y cortisol libre en saliva: 1 vez a la semana durante 4 semanas de línea base antes de la competición Cortisol libre en saliva: al despertar, antes y después de la competición CMJ: antes y después de la competición RPE: después de la competición
Análisis estadístico	Prueba <i>T</i> para muestras relacionadas Coeficiente de correlación de Pearson g de Hedges como estimador del tamaño del efecto $\alpha = 0.05$	ANOVA de medidas repetidas con <i>post-hoc</i> de Bonferroni y estimación de porcentaje de cambio Coeficiente de correlación de Pearson $\alpha = 0.05$	Prueba <i>T</i> para muestras relacionadas Coeficiente de correlación de Pearson $\alpha = 0.05$

^a La carga de entrenamiento se registró mediante la anotación de los kilómetros recorridos, la zona de entrenamiento y el esfuerzo percibido. ^b La producción de fuerza en media sentadilla se midió realizando un test con cargas crecientes en el que se determinó la velocidad media propulsiva, la potencia media propulsiva, el *rate of force development* (RFD) y la Repetición Máxima (RM). *IMC*: índice de masa corporal; *T1500*: mejor tiempo en la prueba de 1500m; *T10000*: mejor tiempo en la prueba de 10000m en ruta; *CMJ*: countermovement Jump (salto con contramovimiento); *RPE*: rate of perceived exertion (escala de esfuerzo percibido, de 0-10); *RFEA*: Real Federación Española de Atletismo.

TABLE 1. Main methodological characteristics of the papers from the present PhD Thesis

	Paper 1	Paper 2	Paper 3
Design	Longitudinal correlation and mean comparisons study (39 weeks, from October to July)	Longitudinal correlation and mean comparisons study (47 weeks, from October to September)	Descriptive, correlations and mean comparisons study with a 4-week baseline
Participants	15 high-level middle and long-distance runners (12 men, 3 women) <i>Age:</i> 26.3±5.1 years <i>BMI:</i> 19.7±1.1 kg/m ² <i>T1500:</i> 3:38-3:58min (men); 4:12-4:23min (women) <i>T10000:</i> 29min24s-31min31s (men); 33min45s-35min56s (women)	15 high-level middle and long-distance runners (12 men, 3 women) <i>Age:</i> 26.3±5.1 years <i>BMI:</i> 19.7±1.1 kg/m ² <i>T1500:</i> 3:38-3:58min (men); 4:12-4:23min (women) <i>T10000:</i> 29min24s-31min31s (men); 33min45s-35min56s (women)	10 high-level middle and long-distance runners (7 men, 3 women) <i>Age:</i> 27.6±5.1 years <i>BMI:</i> 19.6±1.3 kg/m ² <i>T1500:</i> 3:38-3:47min (men); 4:12-4:23min (women) <i>T10000:</i> 29min24s-31min31s (men); 33min45s-35min56s (women)
Measured variables	Training load ^a : daily Salivary-free cortisol and CMJ: weekly Performance (time) in every single official competitions recognised by the RSAF	50m sprint and force production on half-squat ^b : 5 times during the study Training load ^a : daily Salivary-free cortisol: weekly	Salivary-free cortisol and CMJ: once a week during a 4-week baseline prior to the competition Salivary-free cortisol: at the awakening, before and after the competition CMJ: before and after de competición RPE: after the competition
Statistical analyses	Paired-samples T-test Pearson's product moment correlation coefficient Hedge's g for the estimation of the effect sizes $\alpha = 0.05$	Repeated measures ANOVA, Bonferroni <i>post-hoc</i> and estimation of the percent of change Pearson's product moment correlation coefficient $\alpha = 0.05$	Paired-samples T-test Pearson's product moment correlation coefficient $\alpha = 0.05$

^a Training load was measured by registering running km, training zones and rates of perceived effort. ^b Half-squat force production was measured on a test with increasing loads in which mean propulsive velocity, mean propulsive power, rate of force development (RFD) and Repetition Maximum (RM) were determined. *BMI*: body mass index; *T1500*: best time in 1500m; *T10000*: best time in urban 10000m; *CMJ*: countermovement Jump; *RPE*: rate of perceived exertion (0-10 scale); *RSAF*: Royal Spanish Athletics Federation

Para su reclutamiento, en primer lugar, se realizaron diversas entrevistas con el entrenador del grupo en donde se le facilitó un documento con información detallada sobre los objetivos y la metodología del proyecto de investigación. Una vez que el entrenador mostró su conformidad, se realizó otra entrevista con los atletas donde se les explicó, individualmente, las características del proyecto de investigación y las variables que les iban a ser medidas a lo largo de la temporada de competición. Todos los atletas recibieron una copia con información sobre el proyecto de investigación y firmaron un consentimiento informado.

For their recruitment, first, we conducted an interview with the coach where a document with detailed information about the purpose and methodology of the research project was performed. Once the coach expressed its agreement, another interview with the athletes were performed, where they were informed, individually, about the characteristics of the research project and the variables that was going to be measured throughout the whole season. All athletes received a copy of the information document and they signed an informed consent.

Image 2.1 Some of the participants and their coach



Consideraciones éticas

Para garantizar todas las consideraciones éticas necesarias cuando se recopilan muestras biológicas de seres humanos, se presentó el proyecto de investigación de la presente Tesis Doctoral al Comité de Ética de la Universidad Autónoma de Madrid, obteniéndose un informe favorable del mismo. Así, la presente Tesis Doctoral cuenta con la aprobación del Comité de Ética de la Universidad Autónoma de Madrid, con el número CEI-45-889.

Ethical Considerations

To guarantee all ethical considerations needed when human biological samples are collected, the research project of this PhD Thesis was presented to the Ethics Committee of the Autonomous University of Madrid. Thus, this PhD research has the approval of the Ethics Committee of the University of Madrid, number CEI-45-889.

Análisis de las variables medidas

Salto vertical con contramovimiento (CMJ)

Para la medición del CMJ, se utilizó la plataforma de infrarrojos Optojump (Microgate, Italia) y su software Optojump 3.01 para Windows7, el cual ofrece instantáneamente la altura de cada salto en pantalla. Dicha plataforma calcula la altura del salto a través de su tiempo de vuelo, metodología que ha mostrado ser altamente fiable[78].

El CMJ se realizó con las manos en la cintura, realizando un contramovimiento

Analysis of the measured variables

Countermovement jump (CMJ)

For the measurement of the CMJ, an Optojump infrared platform with the software Optojump 3.01 for Windows 7 (Microgate, Italy) were used, which offers instantly the height of each jump. This platform calculates jump height through its flight time, methodology that has shown to be highly reliable [78].

The CMJ was performed with hands on hips, making a countermovement

hasta aproximadamente 90° de flexión de rodillas y manteniendo las rodillas extendidas durante toda la fase de vuelo del salto. Se motivó verbalmente a los atletas para que tratasen de saltar lo más alto posible. Se realizaron 3 intentos y se anotó la media.

to about 90 ° of knee flexion and keeping legs straight throughout the flight phase of the jump. Athletes were verbally encouraged to jump as high as possible. Three trials were performed and the average was recorded.

Image 2.2 Countermovement Jump test



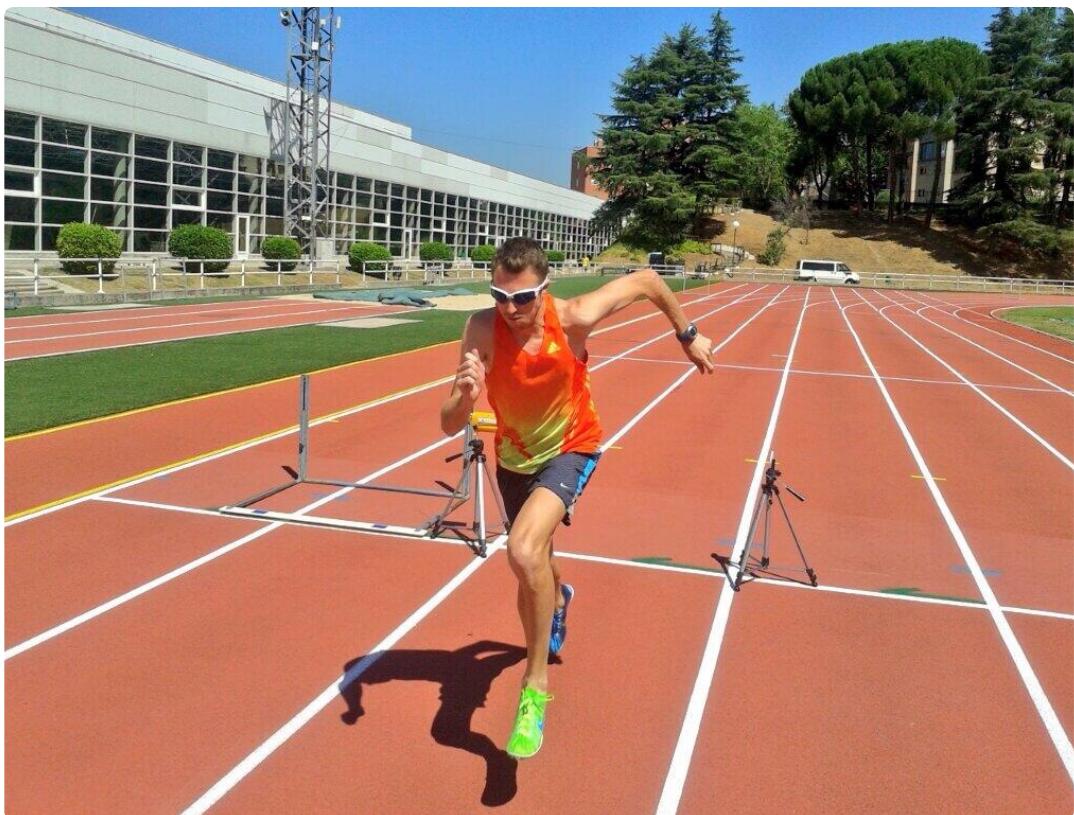
Sprint de 50m

Para la medición del sprint de 50m se utilizó un par de células fotoeléctricas Racetime 2 Light (Microgate, Italia). Dicho par de células se conectaron inalámbricamente a una consola en la cual se registraban los tiempos de cada sprint con una precisión de 0.01s.

50m Sprint

For measuring the 50m sprint, a pair of Racetime 2 Light photocells (Microgate, Italy) was used. Photocells were wirelessly connected to a console in which each sprint times was recorded with an accuracy of 0.01s.

Image 2.3 50m sprint test



El sprint se realizó desde posición estática, 1 metro por detrás de la célula de salida. Se instruyó a los atletas para que corriesen lo más rápido posible los 50m hasta que pasasen por la célula de llegada, situada a 50m en línea recta de la célula de salida. Se anotó el mejor de 2 intentos, los cuales estuvieron separados por 2 minutos de descanso pasivo.

The sprint started from a standstill position, 1 meter behind the start photocell and allowing athletes. Athletes were instructed to run as fast as possible until they passed the stop photocell, located at 50m in a straight line from the start photocell. The best of 2 trials, which were separated by 2 minutes of passive rest was recorded.

Producción de fuerza en media sentadilla

Para la medición de la producción de fuerza en media sentadilla se utilizó un transductor lineal de posición y velocidad T-Force (Ergotech, España) y una máquina Smith (Multipower Fitness Line, España). El T-Force consiste, básicamente, en un cable que se engancha a la barra de pesas y que transmite, cada milisegundo, datos de velocidad y posición gracias a la medición directa de su desplazamiento. Posteriormente, el software T-Force System 2.35 para Windows (Ergotech, España) convierte esos datos de velocidad y posición en muchas otras variables relacionadas con la producción de fuerza, siendo de nuestro interés para la presente Tesis Doctoral, la velocidad media propulsiva, la potencia media propulsiva y

Force production in half-squat

For the measurement of half-squat force production, a T-Force linear position and velocity transducer (Ergotech, Spain) and a Smith machine (Multipower Fitness Line, Spain) was used.

The T-Force is basically a cable that hooks to the barbell which transmits velocity and position data by direct measurement of its displacement to the computer, every millisecond. Subsequently, the T-Force System 2.35 software for Windows (Ergotech, Spain) converts the velocity and position data on many other variables related to force production, being in our interest for the present research, mean propulsive velocity, mean propulsive power and

el Rate of Force Development (RFD), indicador que informa de la capacidad de producir fuerza en la unidad de tiempo[56]. Adicionalmente, el software del T-Force es capaz de estimar la repetición máxima (RM) del sujeto en función de la velocidad del movimiento de las cargas submáximas, metodología que ha mostrado ser altamente precisa [58,59].

Los sujetos realizaron 2 repeticiones con 50, 60, 70, 80, 90 y 100kg en media sentadilla (90° de flexión de rodilla) mientras el T-Force registraba todas las variables de interés relacionadas con la producción de fuerza antes comentadas.

the Rate of Force Development (RFD), an indicator that reports the ability to produce force in the unit time [56]. Additionally, the T-Force software is able to estimate the subject's RM according to the movement velocity of submaximal loads, methodology that has been proved to be highly accurate [58,59].

Subjects performed 2 reps with 50, 60, 70, 80, 90 and 100kg in the half-squat exercise (90 ° knee flexion) while the T-Force recorded all variables related to the force production before mentioned.

Image 2.4 Half-squat incremental test



Los atletas fueron motivados verbalmente para realizar cada repetición a la máxima velocidad posible en la fase concéntrica. Cada serie de 2 repeticiones estuvo separada por 2 minutos de descanso pasivo.

The athletes were verbally encouraged to perform each repetition at maximum concentric velocity. Each set of two repetitions was separated by 2 minutes of passive rest.

Cortisol libre en saliva

Para la medición del cortisol libre en saliva, en primer lugar, se contactó con la Directora del Laboratorio de Bioquímica de la Universidad Politécnica de Madrid (Laboratorio Oficial de la Comunidad de Madrid, número 242), para solicitar ayuda técnica. Hecho esto, se dio acceso al autor de la presente Tesis Doctoral a las instalaciones de dicho laboratorio donde se le enseñó el procedimiento de recolección, congelación, manipulación y análisis de las muestras de cortisol libre en saliva. Así, además de recoger las muestras de saliva durante toda la temporada, el autor de la presente Tesis Doctoral acudió al Laboratorio de Bioquímica de la Universidad Politécnica de Madrid una vez a la semana para colaborar en el análisis de las muestras.

Salivary-free cortisol

For the measurement of the salivary-free cortisol, we first contacted the Head of the Biochemistry Laboratory from the Polytechnic University of Madrid (Official Laboratory number 242 from the Region of Madrid), for technical assistance. After that, the author of this PhD Thesis was allowed to access to the facilities of the laboratory where he was taught the procedure for collecting, freezing, handling and analyzing the saliva samples. Thus, besides collecting the saliva samples throughout the season, the author of this PhD Thesis went to the biochemistry laboratory of the Polytechnic University of Madrid once a week to assist in the analysis of the samples.

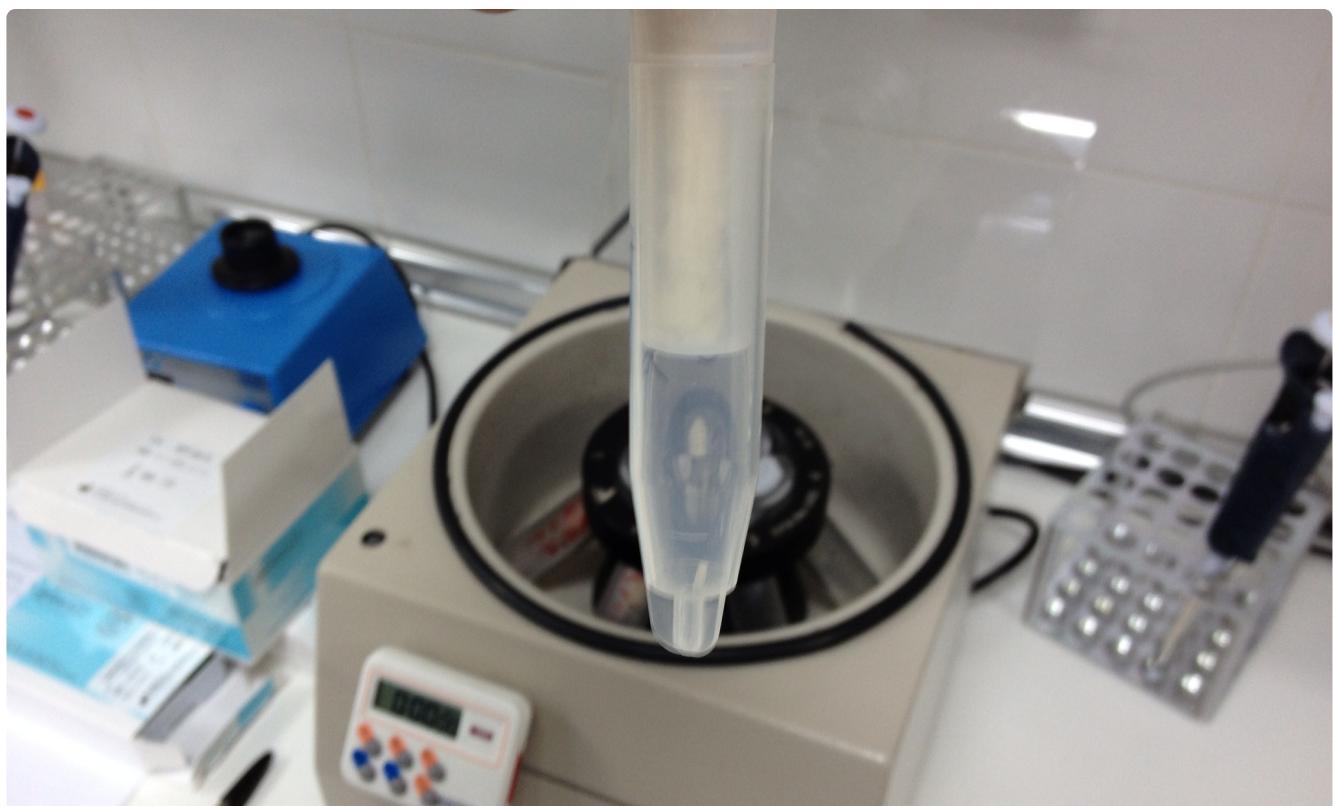
En primer lugar, las muestras de saliva se recogieron utilizando un tubo Salivette (Sarstedt, Alemania), el cual incluía un algodón que los atletas tenían que masticar durante 60 segundos.

Posteriormente, las muestras se congelaron a -20°C hasta el momento de su análisis. Por último, las muestras se centrifugaron a 2500 revoluciones/minuto durante 10 minutos y, finalmente, se procesaron 100µl de saliva precipitada en un kit ELISA (Demeditec Diagnostics, Alemania),

First, the saliva samples were collected using a Salivette tube (Sarstedt, Germany), which included a cotton which athletes had to chew for 60 seconds.

The samples were frozen at -20 ° C until they were analyzed. Finally, samples were centrifuged at 2500rpm for 10 minutes then 100µl of precipitated were analyzed using an ELISA kit (Demeditec Diagnostics, Germany),

Image 2.5 Salivary-free cortisol analysis process



El tuvo Salivette se centrifuga a 2500rpm *The Salivette tube is centrifuged at 2500rpm*

el cual aporta los datos de cortisol libre en saliva mediante análisis de la absorbancia.

Carga de entrenamiento

Para el análisis de la carga de entrenamiento externa, el entrenador del grupo de atletas participantes en la presente Tesis Doctoral nos facilitó los planes de entrenamiento diarios de cada deportista durante toda la temporada. En dichos diarios se registró, individualmente, el número de kilómetros y el ritmo medio de carrera de cada sesión. Los entrenamientos fueron clasificados siguiendo el sistema del entrenador en 3 zonas diferentes de acuerdo al ritmo medio al que esas sesiones se había corrido: la Zona 1 correspondía a los entrenamientos corridos entre 3:45-3:10min/km, Zona 2 entre 3:10-2:50 y Zona 3 2:50 o menos. Dicha elección en el diseño de las zonas se llevó a cabo por la imposibilidad de registrar variables de carga interna como la frecuencia cardíaca. Además, el autor de la presente Tesis Doctoral estuvo presente en los entrenamientos todas las semanas, y cuando un atleta adaptaba su plan de trabajo por lesiones, desplazamientos a competiciones u otras

which provides data of free cortisol saliva by the analysis of absorbance.

Training load

For the analysis of the external training load, the coach of the participants in this PhD research gave us the daily training plans for each athlete throughout the season. In these diaries the number of km and the average pace of each session were recorded for each athlete. Training sessions were classified following the coach's system in 3 different training zones, designed with respect to the average running pace of each session: Zone 1 corresponded to paces between 3:45-3:10, Zone 2 between 3:10-2:50 and Zone 3 2:50 or less. Furthermore, the author of this PhD Thesis attended to the training sessions every week, and when an athlete adapted its workout schedule for injury, travel to competitions or other

situaciones, se comunicaba dicha modificación mediante la aplicación de mensajería instantánea Whatsapp.

Para el análisis de la carga de entrenamiento interna, se utilizó el session-RPE de 0 a 10 [30]. Véase la Tabla 2. Para ello, al final de cada sesión de entrenamiento se preguntó a los atletas, “¿Cómo de dura ha sido la sesión de entrenamiento, siendo 0 muy suave, y 10 extremadamente dura?”.

Cuando los atletas no pudieron asistir al Centro de Alto Rendimiento y entrenaron en otras instalaciones, los RPE se comunicaban mediante la aplicación Whatsapp.

situations, it was communicated by the instant messaging application WhatsApp.

For the analysis of the internal training load, the session-RPE, 0 to 10 scale, was used [30]. See Table 2. To do this, at the end of each training session the athletes were asked, "How hard was the training session, where 0 is very very soft, and 10 extremely hard?".

When athletes could not attend to the High Performance Center and trained at other facilities, the RPE was communicated through Whatsapp application.

TABLA 2. Escala de esfuerzo percibido utilizada (session-RPE 0-10). Versión en castellano traducida de la original de Foster [30]

TABLE 2. Scale of rate of perceived exertion used (session-RPE 0-10) [30]

¿Cómo de dura ha sido la sesión de entrenamiento, competición?

¿How hard was the training/competition session?

0	Reposo	<i>Rest</i>
1	Muy, muy suave	<i>Very, very light</i>
2	Suave	<i>Light</i>
3	Moderada	<i>Moderate</i>
4	Algo dura	<i>Somewhat hard</i>
5	Dura	<i>Hard</i>
6		
7	Muy dura	<i>Very hard</i>
8		
9		
10	Extremadamente dura	<i>Extremely hard</i>

Resultados Principales

Main Results



A continuación, se muestran algunos de los resultados principales derivados de los estudios que componen la presente Tesis Doctoral. Dichos resultados están ordenados según el artículo en el que se han publicado. Para más detalle, véase la sección “Results” de cada uno de los artículos que componen la presente Tesis Doctoral, disponibles en la sección Apéndices.

In the next pages we show some of the main results founded on the studies which compose the present PhD Thesis. These results are sorted by the paper in which they are published. For further details, please see the “Results” section on each paper which compose the present PhD Thesis, available on the Appendices section.

Artículo 1 Paper 1

Balsalobre-Fernández C, Tejero-González CM, del Campo-Vecino J. Relationships between Training Load, Salivary Cortisol Responses and Performance during Season Training in Middle and Long Distance Runners. PLoS One. 2014;9(8):e106066.

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Relationships between Training Load, Salivary Cortisol Responses and Performance during Season Training in Middle and Long Distance Runners

Carlos Balsalobre-Fernández*, Carlos M^a Tejero-González, Juan del Campo-Vecino

Department of Physical Education, Sport and Human Movement, Autonomous University of Madrid, Madrid, Spain

En este estudio, se analizaron las relaciones existentes entre la carga de entrenamiento (medida mediante el RPE, los kilómetros y la zona de entrenamiento semanales), los niveles de cortisol libre en saliva y el rendimiento neuromuscular (mediante el test de salto vertical CMJ) durante toda una temporada de entrenamiento en corredores de mediodfondo y fondo de alto nivel. Además, se estudiaron los niveles de dichas variables antes de la mejor y peor competición de la temporada con la intención de obtener unos niveles óptimos que puedan ayudar en la monitorización del estado de preparación de los deportistas.

In this study we analyzed the relationships between training load (measured through RPE and weekly km and training zone), salivary-free cortisol levels and neuromuscular performance (using the countermovement jump) in high-level middle and long distance runners throughout an entire training season. Furthermore, the levels of these variables before the best and worst competitions of the season were studied in order to obtain descriptive optimal levels which could help monitoring the readiness of the athletes.

TABLA 3. Correlaciones entre los valores medios de la temporada en las variables estudiadas*TABLE 3. Correlations between the season average values of the studied variables*

	Session-RPE	Cortisol	KM run	Training zone
CMJ	-0.489*	-0.777**	0.133	-0.231
Session-RPE		0.551*	0.168	-0.130
Cortisol			-0.051	-0.028
KM run				-0.599*

* $p < 0,05$; ** $p < 0,001$; Abreviaturas: CMJ = countermovement jump; session-RPE = escala de esfuerzo percibido por sesión; Cortisol = cortisol libre en saliva; KM run = número de kilómetros corridos por semana

* $p < 0,05$; ** $p < 0,001$; Abbreviations: CMJ = countermovement jump; session-RPE = session rate of perceived exertion; Cortisol = salivary-free cortisol; KM run = number of KM trained per week

En primer lugar, se encontraron correlaciones significativas entre los valores medios de la temporada del CMJ y el cortisol ($r=-0.777$, $p<0.001$), entre el CMJ y el session-RPE ($r=-0.489$, $p=0.049$) y el session-RPE y el cortisol ($r=0.551$, $p=0.025$). Véase la Tabla 3. En segundo lugar, el análisis de los valores medios semanales a lo largo del estudio mostró que el CMJ correlaciona significativamente con el session-RPE ($r=-0.426$, $p=0.012$), el cortisol ($r=0.556$, $p<0.001$), los kilómetros recorridos ($r=-0.593$, $p<0.001$) y la zona de entrenamiento ($r=0.437$, $p=0.007$). Por otro lado, los kilómetros recorridos por semana se correlacionaron significativamente con el session-RPE ($r=0.444$, $p=0.009$) y los niveles de cortisol ($r=-0.366$, $p=0.017$).

First, we found significant correlations were found between season average CMJ and cortisol ($r=-0.777$, $p<0.001$), CMJ and session-RPE ($r=-0.489$, $p=0.049$) and session-RPE and cortisol ($r=0.551$, $p=0.025$) values. See Table 3 for more details. Secondly, the analysis of the average weekly values of the variables throughout the whole season showed that CMJ scores correlate significantly with session-RPE ($r=-0.426$, $p=0.012$), cortisol ($r = 0.556$, $p<0.001$), km run ($r = -0.593$, $p<0.001$) and training zone ($r = 0.437$, $p = 0.007$). Also, km run correlates significantly with session-RPE ($r = 0.444$, $p = 0.009$) and cortisol levels ($r = -0.366$, $p = 0.017$).

Por último, cuando se compararon los valores de las variables medidas la semana previa a la mejor (SB) y peor (SW) competición de la temporada, se observó que los valores de CMJ antes de la SB fueron significativamente mayores (+8.5%, $g=0.65$, $p<0.001$). Además, los valores de session-RPE antes de la SB fueron significativamente más bajos (-17.2%, $g=0.94$, $p=0.022$), no encontrándose diferencias significativas en el cortisol libre en saliva, los kilómetros recorridos ni la zona de entrenamiento. Véase la Figura 1 para más detalles.

Finally, when comparing the values for the variables measured the week before the season-best (SB) and season-worst (SW) competition performances, it was found that the CMJ scores prior to the SB was significantly higher than the CMJ score prior to the SW (+ 8.5%, $g = 0.65$, $p < 0.001$). Also, the session-RPE for the week before the SB was significantly lower than the session-RPE for the week before the SW (-17.6%, $g = 0.94$, $p = 0.022$), but no significant differences between salivary free cortisol, km run or training zone values. See Figure 1 for more details.

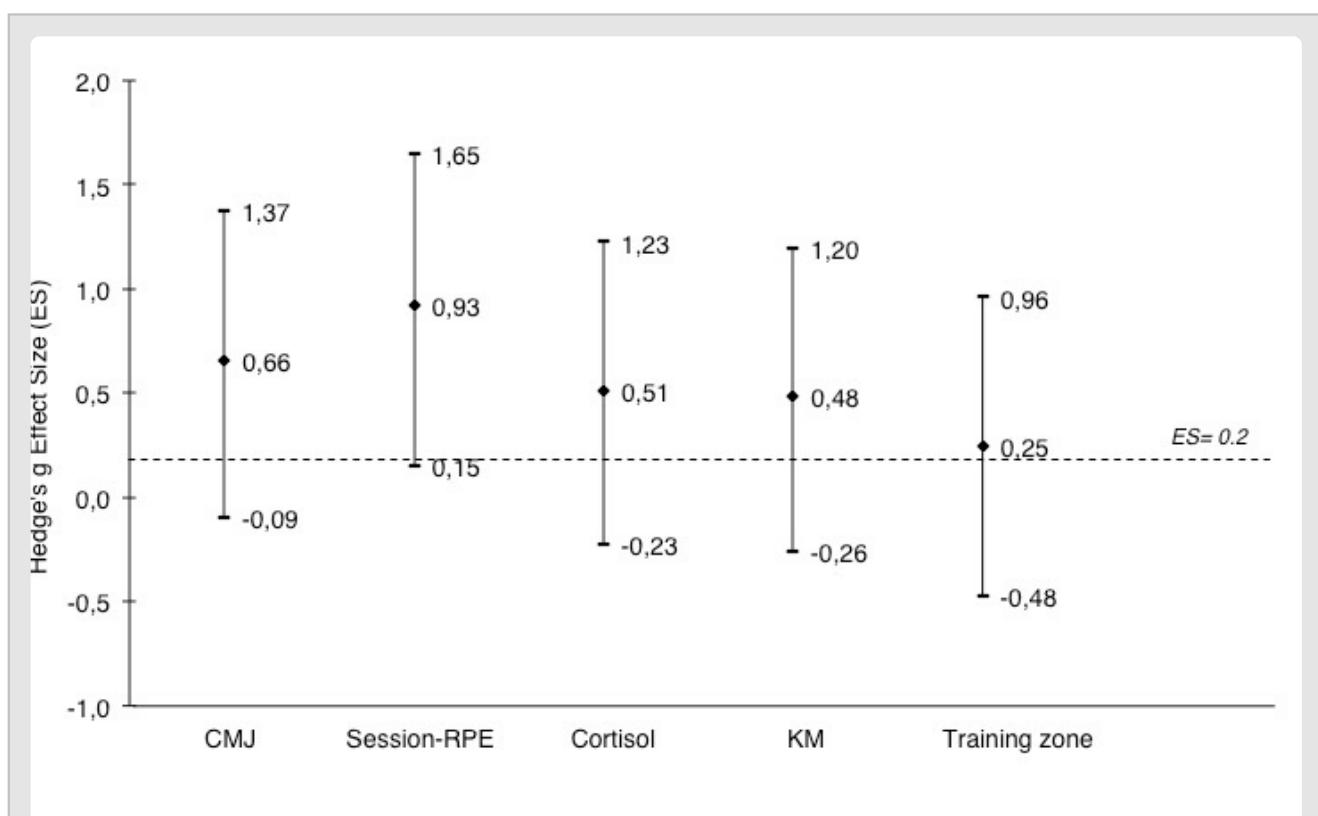


Figura 1. Tamaños del efecto de las diferencias entre la mejor y peor competición de la temporada (con intervalos de confianza al 95%)

Figure 1. Standardized effect sizes of the difference between season best and worst competitions (plus 95% Confidence Intervals)

Artículo 2 *Paper 2*

Balsalobre-Fernández C, Tejero-González CM, del Campo-Vecino J. Seasonal strength performance and its relationship with training load on elite runners. *J Sport Sci Med.* 2015;14(1); 9-15.

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Research article

Seasonal Strength Performance and Its Relationship with Training Load on Elite Runners

Carlos Balsalobre-Fernández¹✉, Carlos M. Tejero-González¹ and Juan del Campo-Vecino¹

¹ Autonomous University of Madrid, Department of Physical Education, Sport and Human Movement, Madrid, Spain

En este estudio se midió la capacidad de producir fuerza de los miembros inferiores de los atletas en cuatro periodos de entrenamiento diferentes a lo largo de la temporada competitiva, analizándose tanto su evolución en el tiempo como su relación con la carga de entrenamiento y los niveles de cortisol libre en saliva.

In this study, athlete's lower limbs force production was measured in four different training periods throughout the competitive season, analyzing its time-coursa and its relationships with training load and salivary-free cortisol levels.

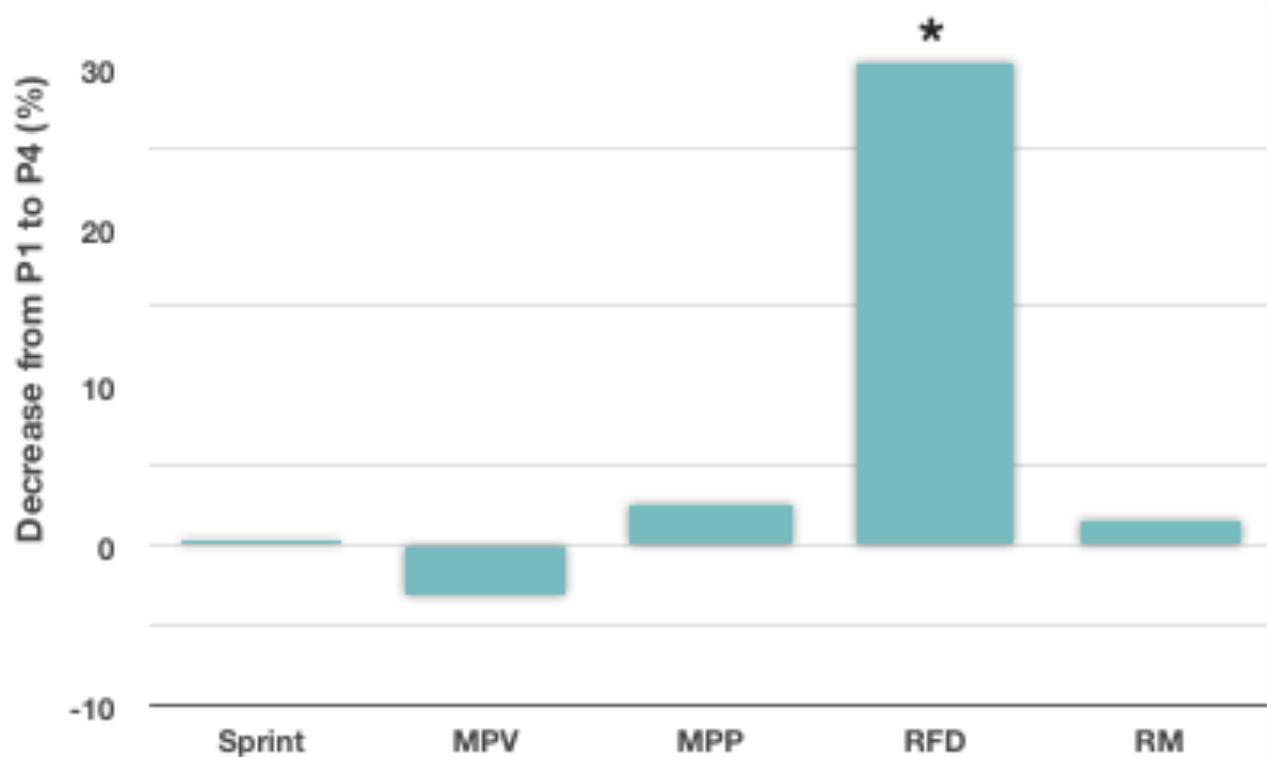


Figura 2. Decreto de las variables desde el inicio (P1) hasta el final (P4) de la temporada. Abreviaturas: Sprint=sprint de 50m; MPV=velocidad media propulsiva en media sentadilla; MPP=potencia media propulsiva en media sentadilla; RFD=rate of force development en media sentadilla; RM=repetición máxima; * $p < 0.05$

*Figure 1. Decrease from the beginning (P1) to the end (P4) of the season on the strength-related variables studied. Abbreviations: Sprint=50m sprint; MPV=half-squat mean propulsive velocity; MPP=half-squat mean propulsive power; RFD=half-squat rate of force development; RM=Repetition Maximum; * $p < 0.05$*

Al analizar la evolución de los niveles de fuerza a lo largo de los períodos de entrenamiento, el ANOVA de medidas repetidas mostró que no hubo cambios significativos en las siguientes variables entre el principio (P1) y el fin (P4) de la temporada: sprint de 50m, velocidad media propulsiva (MPV), potencia media propulsiva (MPP) o la RM ($p > 0.05$). Sin embargo, se observó un decreto significativo, de un 30.2%, en la RFD en media sentadilla ($p = 0.005$). Véanse las Figuras 2 y 3.

When analyzing the time-course of the strength characteristics of the athletes throughout the season, the repeated measures ANOVA reported that there were no significant differences in the following variables: time in the 50-metre sprint, mean propulsive velocity (MPV), mean propulsive power (MPP) or RM of half-squats (all > 0.05). In contrast, a 30.2% decrease in the RFD of half-squats ($p = 0.005$) was observed between the beginning (P1) and the end (P4) of the season. See Figures 2 and 3.

Teniendo en cuenta los valores medios durante la temporada en los distintos períodos de entrenamiento, se encontraron diversas correlaciones significativas. El RPE correlacionó significativamente con la MPV ($r = -0.650, p = 0.004$), MPP ($r = -0.602, p = 0.009$) y la RM ($r = -0.650, p = 0.004$) en media sentadilla, así como con el sprint de 50m ($r = 0.560, p = 0.015$). Por su parte, el cortisol libre en saliva correlacionó significativamente con el sprint de 50m ($r = 0.737, p < 0.001$) y la RM en media sentadilla ($r = -0.514, p = 0.025$).

Based on the season-long average value of each variable, several correlations were apparent. RPE correlated significantly with MPV ($r = -0.650, p = 0.004$), MPP ($r = -0.602, p = 0.009$) and RM ($r = -0.650, p = 0.004$) of half-squats, and also with the 50-metre sprint ($r = 0.560, p = 0.015$). Meanwhile, salivary free cortisol correlated significantly with the 50-metre sprint ($r = 0.737, p < 0.001$) and the half-squat RM ($r = -0.514, p = 0.025$).

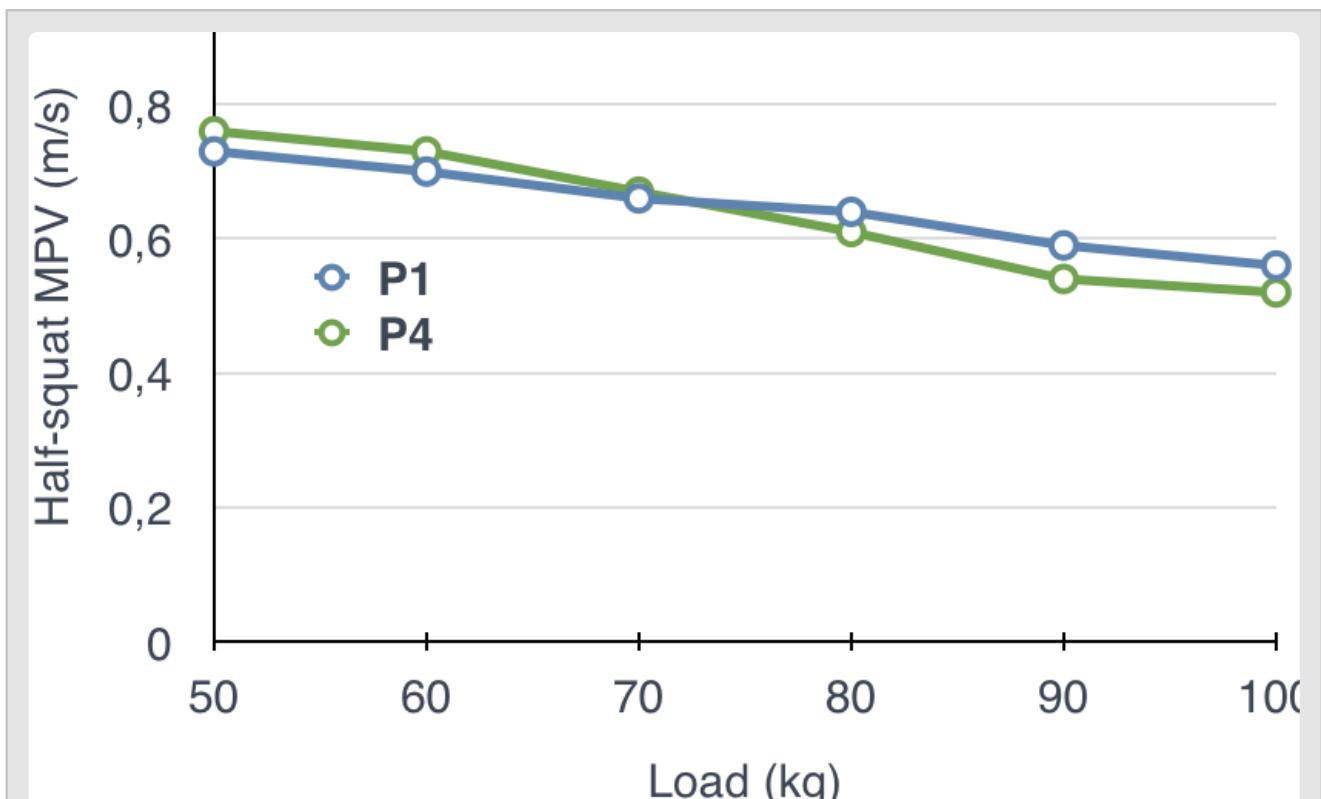


Figura 3. Comparación de la velocidad media propulsiva (MPV) producida ante cada carga en media sentadilla al principio (P1) y final (P4) de la temporada.

Figure 3. Comparison of the mean propulsive velocity (MPV) produced with each load on the half-squat exercise at the beginning (P1) and at the end (P4) of the season.

Por último, la zona de entrenamiento correlacionó significativamente con el sprint de 50m ($r = -0.463$, $p = 0.041$). Véase la Tabla 4 para más detalles.

Finally, the average training zone correlated with the 50-metre sprint ($r = -0.463$, $p = 0.041$). See Table 4 for more details.

TABLA 4. Correlaciones entre los valores medios de los períodos en las variables estudiadas

TABLE 4. Correlations between the training periods average values of the studied variables

	Sprint	MPV	MPP	RFD	RM	CORT	RPE	KM	ZONE
Sprint	---	-0.769**	-0.795**	-247	-0.823**	0.737**	0.560*	0.072	-0.463*
MPV		---	0.910**	0.462*	0.918**	-335	-0.650**	-0.142	0.288
MPP			---	0.478*	0.960**	-430	-0.602**	0.013	0.269
RFP				---	414	-33	-415	-0.117	-0.192
RM					---	-0.514*	-0.650**	-0.134	0.408
CORT						---	318	0.053	-0.528*
RPE							---	-0.034	-0.082
KM								---	-0.597**

* $p < 0.05$; ** $p < 0.001$; Abreviaturas: Sprint=sprint de 50m; MPV=velocidad media propulsiva en media sentadilla; MPP=potencia media propulsiva en media sentadilla; RFD=rate of force development en media sentadilla; RM=repetición máxima; RPE = escala de esfuerzo percibido por sesión; CORT = cortisol libre en saliva; KM=número de kilómetros corridos; ZONE=zona de entrenamiento

* $p < 0.05$; ** $p < 0.001$; Abbreviations: Sprint=50m sprint; MPV=half-squat mean propulsive velocity; MPP=half-squat mean propulsive power; RFD=half-squat rate of force development; RM=Repetition Maximum; RPE = session rate of perceived exertion; CORT=salivary-free cortisol; KM=number of KM trained per week; ZONE=training zone

Artículo 3 Paper 3

Balsalobre-Fernández C, Tejero-González CM, del Campo-Vecino J. Homonal and Neuromuscular Responses to High Level Middle and Long-Distance Competition. Int J Sports Physiol Perform. 2014;9(5):839-44.

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 ORIGINAL INVESTIGATION

Hormonal and Neuromuscular Responses to High-Level Middle- and Long-Distance Competition

Carlos Balsalobre-Fernández, Carlos M^a Tejero-González, and Juan del Campo-Vecino

En este estudio se analizaron los efectos que el Campeonato de España de Atletismo Absoluto, considerada la competición más importante de la temporada, tiene sobre los niveles hormonales, el rendimiento neuromuscular y la percepción de esfuerzo en corredores de mediofondo y fondo de alto nivel. Por un lado, se compararon los valores en dichas variables el día de la competición con los obtenidos durante una línea base de 4 semanas previas a la carrera. Por otro lado, se analizaron los cambios pre-post competición en los niveles de salto vertical CMJ y cortisol libre en saliva, así como las relaciones entre dichos cambios .

In this study we analyzed the hormonal, neuromuscular and perceived effort responses produced by the Spanish Track & Field National Championships, considered the most important competition of the season, in high-level middle and long distance runners. First, the values of these variables measured on the competition day were compared with those obtained during a 4-week baseline prior the race. Second, countermovement jump and salivary-free cortisol pre-post competition changes and the relationships between these changes were analyzed.

En primer lugar, se observó que los niveles de cortisol ($+117.5\%$, $g = 1.59$, $p < 0.001$) y de CMJ realizado antes de la competición ($+6.5\%$, $g = 0.47$, $p < 0.001$) fueron significativamente más altos el día de la competición que durante la línea base. Véase la Figura 4. De hecho, este incremento del cortisol correlacionó significativamente con el incremento del CMJ ($r=0.688$, $p=0.010$).

First, it was observed that the values of basal cortisol ($+117.5\%$, $g = 1.59$, $p < .001$) and CMJ (performed before the race) ($+6.5\%$, $g = 0.47$, $p < .001$) were significantly higher on competition day than during the baseline period. See Figure 4. Furthermore, the increase on the cortisol levels was correlated with the increase of the CMJ height ($r=0.688$, $p=0.010$).

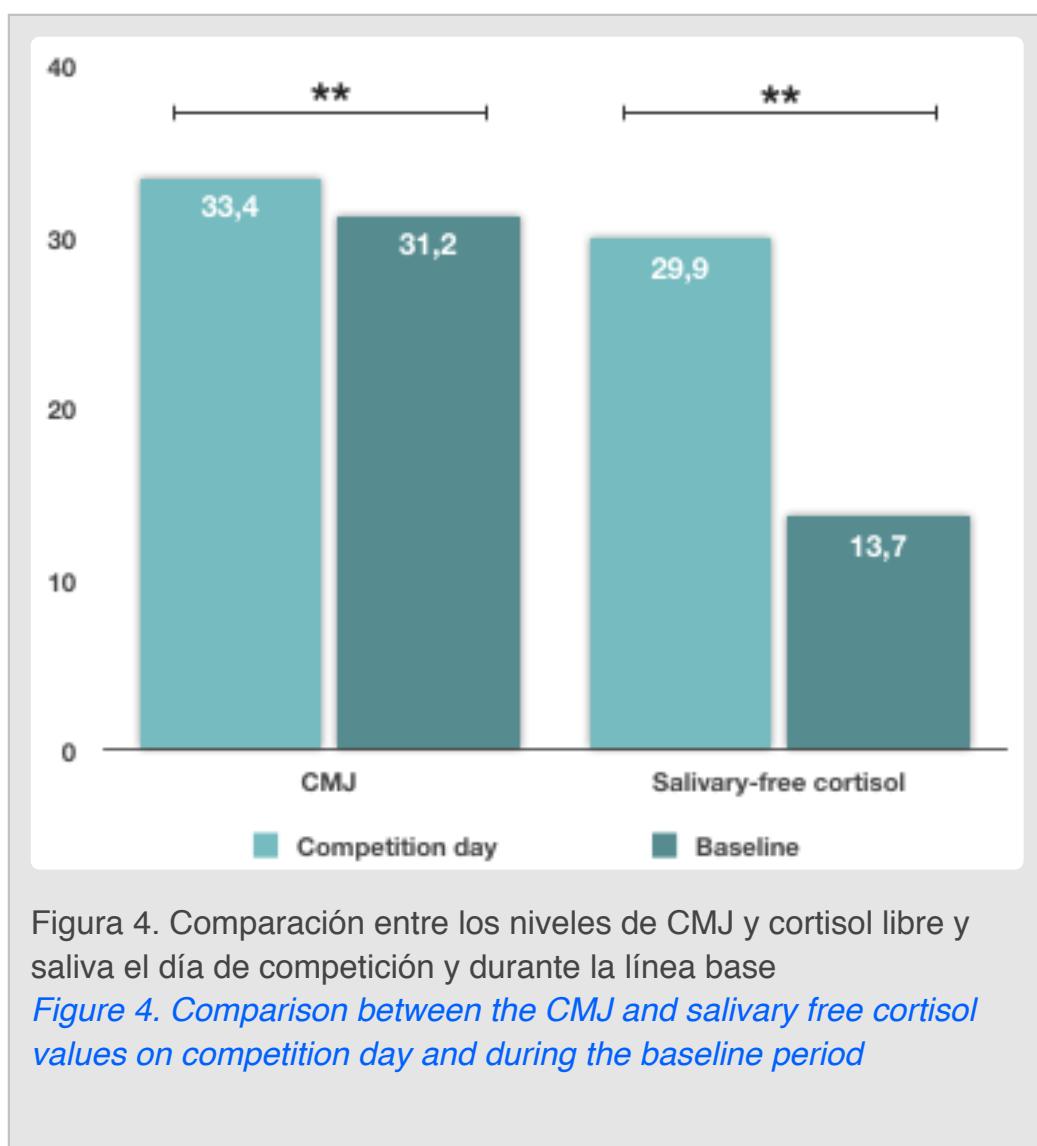


Figura 4. Comparación entre los niveles de CMJ y cortisol libre y saliva el día de competición y durante la línea base

Figure 4. Comparison between the CMJ and salivary free cortisol values on competition day and during the baseline period

En segundo lugar, el CMJ disminuyó significativamente después de la competición (-3.9% , $g = 0.34$, $p = 0.025$), mientras que el cortisol se incrementó significativamente ($+98.3\%$, $g = 0.82$, $p = 0.027$) en comparación con las mediciones realizadas 90min antes de la carrera. Este decremento del CMJ correlacionó significativamente con el incremento del cortisol ($r=0.782$, $p=0.011$). Véase la Figura 5.

Secondly, after the competition CMJ height decreased significantly (-3.9% , $g = 0.34$, $p = 0.025$), while cortisol levels were significantly higher ($+98.3\%$, $g = 0.82$, $p = 0.027$) in comparison with the measurements taken 90 minutes before the race. Moreover, that decrease on the CMJ height was correlated with the increase of the cortisol levels ($r=0.782$, $p=0.011$). See Figure 5.

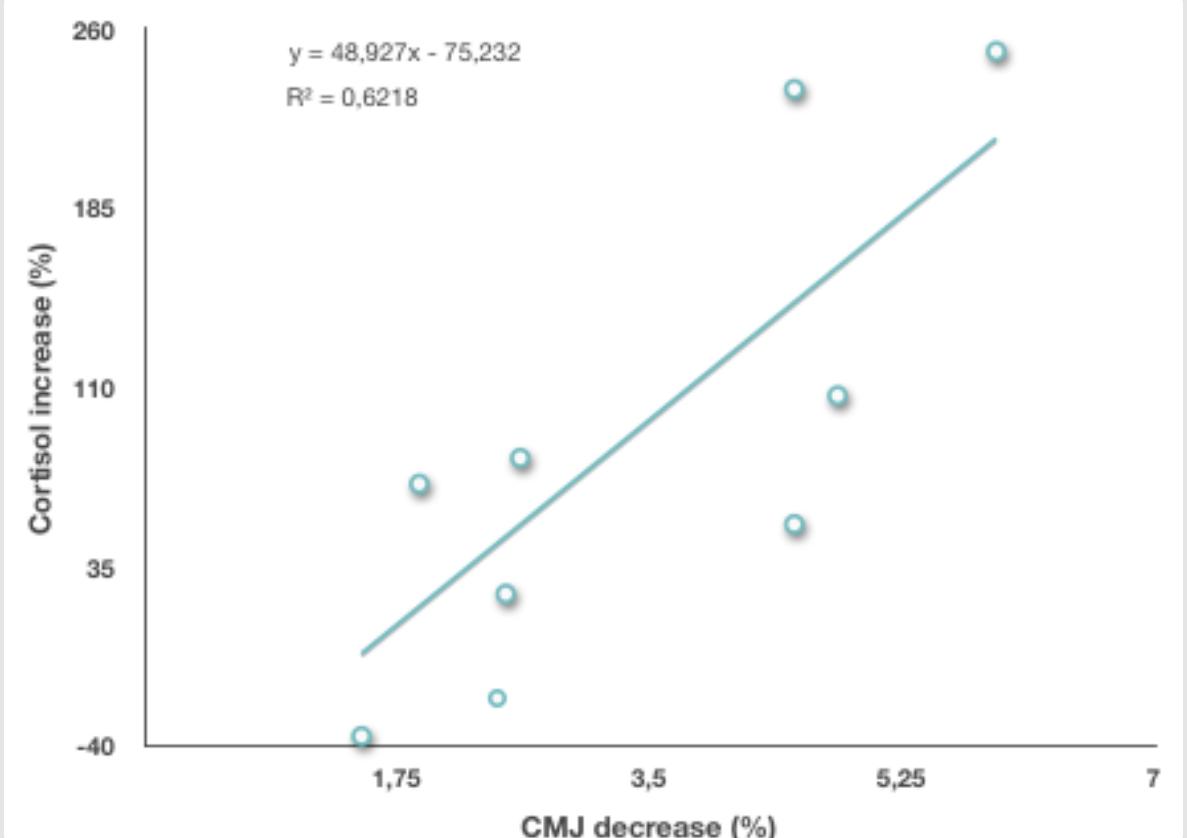


Figura 5. Correlación entre el decremento del CMJ y el incremento del cortisol pre-post competición

Figure 5. Correlation between the pre-post competition CMJ decrease and cortisol increase

Por último, se encontraron correlaciones positivas y significativas entre (1) la disminución post-competición del CMJ y el esfuerzo percibido (RPE) medido después de la competición ($r = 0.762$, $p = 0.002$), y (2) el incremento post-competición de los niveles de cortisol libre en saliva y la distancia de competición ($r = 0.67$, $p = 0.034$).

Finally, significant and positive correlations were observed between (1) the CMJ decrease and the RPE measured right after the competition ($r = 0.762$, $p = .002$), and (2) the postcompetition increase in salivary free cortisol levels and the competition distance ($r = 0.67$, $p = .034$).

Discusión

Discussion, limitations and prospects



La presente Tesis Doctoral muestra resultados novedosos respecto a la monitorización del proceso de entrenamiento, la fatiga y los niveles de fuerza en corredores de mediofondo y fondo de alto nivel a lo largo de toda una temporada. El entrenamiento deportivo de alto nivel requiere de numerosas sesiones de trabajo semanales y de intensidades de esfuerzo, en ocasiones, máximas [1,36-38,40,177]. De esta forma, la monitorización longitudinal de diversas

This PhD Thesis shows new results regarding the monitoring of the training process, fatigue and strength levels in high-level middle and long-distance runners throughout an entire season. High-level sports training requires numerous sessions per week and very high perceived efforts (sometimes, maximal) [1,36-38,40,177]. Thus, the longitudinal monitoring of some

variables relacionadas con el estado de forma, la fatiga y las cargas de entrenamiento se ha propuesto como una metodología necesaria para evitar los estados de overreaching o sobreentrenamiento [121,146], encontrándose en la literatura numerosos estudios con diversos tipos de deportistas [23,38,40,86,178-181]. Por ejemplo, Cormack et al [77] midieron el rendimiento en el CMJ y el ratio testosterona/cortisol en saliva durante 22 semanas de competición en jugadores de fútbol australiano profesionales con el objetivo de determinar los períodos de mayor fatiga neuromuscular.

Sin embargo, los estudios longitudinales con atletas de alto nivel son muy escasos y, en el caso de corredores de mediofondo y fondo, prácticamente inexistentes [37,40]. La experiencia nos dice que es complicado que los deportistas de alto nivel accedan a participar en tomas de datos que requieran de mediciones sistemáticas y prolongadas en el tiempo, dificultando así en gran medida la recolección continua de muestras. Cuando se quiere medir el estado de forma mediante pruebas de rendimiento como el consumo máximo de oxígeno o el test de Repetición Máxima (RM), el elevado grado de fatiga que generan dichos test

variables related to fitness, fatigue and training load has been proposed as a needed methodology to avoid overreaching or overtraining states [121,146], with several studies in the literature studying this topic with different athletes [23,38,40,86,178-181]. For example, Cormack et al [77] measured the performance in the CMJ and the testosterone / cortisol ratio in saliva during 22 weeks of competition in professional Australian football players to determine the periods of greater neuromuscular fatigue.

However, longitudinal studies with elite athletes are very scarce and, in the case of middle and long-distance runners, almost non-existent [37,40]. Experience tells us that it is difficult that high-level athletes agree to participate in data collections that require systematic and prolonged measurements over time, making it difficult to collect samples for a long period. When physical performance is measured with VO₂Max or RM tests, the high degree of fatigue these tests generate

[59,62,182] podría suponer una interferencia notable con el proceso de entrenamiento de los deportistas si lo realizasen, por ejemplo, una vez a la semana. Probablemente, este sea uno de los motivos por los que la inmensa mayoría de estudios que han monitorizado diversas variables fisiológicas en deportistas de élite se han limitado a realizar 3-6 mediciones por temporada [23,37,107,179,183].

Sin embargo, las ventajas que supone monitorizar el proceso de entrenamiento son de indudable utilidad para entrenadores y deportistas, pues ayudan a anticipar el descenso sistemático del rendimiento u overreaching [2,16,17,113,121]. Por ello, la utilización de metodologías no invasivas que permiten monitorizar sistemáticamente el proceso de entrenamiento está siendo el foco de atención de numerosos estudios [25,27,29,184]. De hecho, la tecnología está constantemente avanzando hacia dispositivos cada vez menos agresivos y más amigables para los deportistas, con sensores incorporados en los smartphones o en las propias prendas de vestir [185,186]. Por ejemplo, en unos pocos meses saldrán al mercado unas medias con unos sensores incorporados capaces de medir la frecuencia cardíaca y

[59,62,182] could produce a significant interference with the training process of athletes if they are used, for example, once a week. This is probably one of the reasons why the vast majority of studies that have monitored several physiological variables in elite athletes have performed just 3-6 measurements per season [23,37,107,179,183].

However, the advantages of monitoring the training process are undoubtedly useful for coaches and athletes, as they help to anticipate the systematic decline in performance or overreaching [2,16,17,113,121]. Therefore, the use of noninvasive methodologies to systematically monitor the training process is still the focus of numerous studies [25,27,29,184]. In fact, technology is constantly advancing towards less aggressive and more friendly devices, such as smartphones or wearables (i.e., clothes with different built-in sensors) [185,186]. For example, in a few months it will be available special stockings with embedded sensors capable of measuring heart rate and

el umbral de lactato en carrera por menos de 200€ (BSX Athletics, USA). Estas innovaciones, impensables hace unos pocos años, podrán ayudar a conocer las respuestas individuales de los deportistas al ejercicio y a programar con mayor precisión las cargas de entrenamiento.

En definitiva, la utilización de metodologías no invasivas, asequibles, eficientes y a la vez respaldadas por la comunidad científica permiten obtener información del estado de forma o del grado de fatiga de los deportistas de alto nivel de manera sistemática y sin apenas interferir en el proceso de entrenamiento. En este sentido, uno de los principales resultados de la presente Tesis Doctoral es la relación que el CMJ y el RPE tienen con el cortisol libre en saliva, los kilómetros semanales corridos, la zona de entrenamiento o los niveles de fuerza en corredores de mediofondo y fondo de alto nivel. Específicamente, el Artículo 1 de la presente Tesis Doctoral muestra una correlación negativa y estadísticamente significativa ($r = -0.777$, $p < 0.001$) entre los niveles medios de CMJ y los niveles medios de cortisol libre en saliva a lo largo de toda la temporada de entrenamiento. Un estudio previo con jugadores de fútbol encontró correlaciones significativas entre los niveles de CMJ y cortisol libre en saliva

lactate threshold while running for less than 200 € (BSX Athletics, USA). These innovations, unthinkable a few years ago, may help to know the athletes' individual responses to exercise and to program training loads in a more accurate way.

Definitely, the use of non-invasive, affordable, efficient and scientifically validated methodologies allows to obtain information about the degree of fatigue of high-level athletes in a systematic way without interfering in the training process. In this sense, one of the main results of this PhD Thesis is the relationships that the CMJ and RPE have with salivary-free cortisol, training volume, training zones or the strength levels in high-level middle and long-distance runners. Specifically, the Paper 1 of the present PhD Thesis shows a negative and statistically significant correlation ($r = -0.777$, $p < 0.001$) between the season average levels of CMJ and salivary-free cortisol. A previous study with soccer players found significant correlations between the levels of CMJ and salivary-free cortisol

durante 11 semanas de entrenamiento, concluyendo que los jugadores con mayores niveles de cortisol al inicio de la temporada tendían significativamente a reducir su potencia muscular durante el periodo de estudio [161]. Sin embargo, hasta donde llega nuestro conocimiento, ésta es la primera vez que se analizan las relaciones entre el CMJ y el cortisol libre en saliva en corredores de mediofondo y fondo de alto nivel.

Sin embargo, cuando analizamos los valores de CMJ y cortisol libre en saliva semanalmente, y no en valores medios de la temporada, el sentido de la correlación cambia: se observa una correlación positiva y estadísticamente significativa ($r = 0.556$, $p < 0.001$) entre dichas variables. Relaciones similares se han descrito previamente en la literatura, aunque con deportistas especializados en fuerza [170,187]. En concreto, se ha demostrado que los niveles de cortisol correlacionan positivamente con el salto vertical en jugadores de rugby profesionales [187] o con el rendimiento en competición en levantadores de alto nivel [170]. Así, aunque los niveles de cortisol a largo plazo puedan influir negativamente en el rendimiento físico [161], parece que los valores agudos de dicha hormona se relacionan con

during 11 weeks of training, concluding that players with higher levels of cortisol at the start of the season tended to significantly reduce their muscular power during the study period [161]. However, to the best of our knowledge, this is the first study analyzing the relationship between the CMJ and salivary-free cortisol in high-level middle and long-distance runners.

However, when analyzing the weekly values of the CMJ and salivary-free cortisol instead of the season average values, the direction of the correlation changes: a positive and statistically significant correlation ($r = 0.556$, $p < 0.001$) is observed between these variables. Similar relationships have been previously described in the literature, although with strength-specialized athletes [170,187]. Specifically, it has been demonstrated that cortisol levels positively correlate with the vertical jump in professional rugby players [187] or competition performance on high level weight-lifters [170]. Thus, although long-term cortisol levels may adversely affect physical performance [161], it seems that acute values of such hormone are related to

estados de incremento de la capacidad de producir fuerza en el mismo día, aunque los mecanismos por los cuales la dirección de estas relaciones cambia son confusos [3,161,187]. Así, es necesaria más investigación para explicar los motivos por los cuales el cortisol puede relacionarse en direcciones opuestas con la producción de fuerza. En cualquier caso, nuestro estudio amplía el conocimiento existente mostrando por primera vez la relación entre los niveles de CMJ y cortisol libre en saliva durante una temporada en corredores de mediofondo y fondo de alto nivel.

Por su parte, la carga de entrenamiento también ha mostrado relaciones con el CMJ que merecen ser mencionadas. Por un lado, los niveles medios de CMJ correlacionaron significativamente ($r = -0.489$, $p < 0.05$) con los niveles medios de RPE durante toda la temporada, de tal forma que aquellos atletas que han entrenado con unas sensaciones de esfuerzo más altas tienden, significativamente, a tener valores promedio de salto más bajos. Por otro lado, cuando analizamos los datos semanalmente, y no como media de la temporada, se observó de nuevo una correlación negativa y estadísticamente significativa entre el valor medio semanal

states of increased strength capabilities within the same day, although the mechanisms by which the direction of these relations changes are unclear [3,161,187]. Thus, more research is needed to explain the reasons why cortisol may relate in opposite directions with force production. In any case, our study extends existing knowledge, showing for the first time s the relationships between the CMJ and salivary-free cortisol levels during a whole season in high-level middle and long-distance runners.

Meanwhile, the training load has also shown significant relations with the CMJ which worth to be mentioned. First, the season average levels of CMJ and RPE are significantly correlated ($r = -0.489$, $p <0.05$), so that athletes who have trained with a higher perceived effort tend to have lower CMJ values. Second, when we analyzed the weekly values instead of the season average's, we observed again a negative and statistically significant correlation between the average weekly

de RPE y el CMJ medido esa semana. Es más, el valor semanal de CMJ también correlacionó significativamente con los kilómetros recorridos y la zona de entrenamiento, siendo las semanas con menos RPE, menos kilómetros recorridos y mayor zona de entrenamiento aquellas con mayores valores de CMJ. Por último, se observó que los niveles semanales de RPE correlacionaron con los kilómetros recorridos, siendo las semanas con mayor número de kilómetros las que producen sensaciones de esfuerzo superiores. Diversos autores proponen que los entrenamientos tradicionales con volúmenes elevados son menos adecuados para el incremento del rendimiento en atletas de resistencia muy entrenados que aquellos organizados en bloques de menor cantidad y mayor intensidad de trabajo [37,188-190]. Por ejemplo, se ha comprobado que una temporada periodizada en bloques, reduciendo un 50% el volumen de la temporada anterior produce incrementos mayores en la potencia y la velocidad de remo en un grupo de remeros de élite (entre los que se incluyen 2 Campeones Olímpicos) [188]. Del mismo modo, se sabe que las intensidades de esfuerzo excesivamente elevadas pueden inducir unos estados de fatiga aguda o incluso sobreentrenamiento que producen

RPE and the CMJ height measured that week. Moreover, weekly CMJ height also correlated significantly with weekly km and training zone values. Thus, the weeks with lower RPE, km and higher training zones values tend to have higher CMJ levels. Finally, it was observed that the weekly RPE levels correlated with the total km of that week, being the weeks with the highest number of km the ones that produced greater perceived efforts. Several authors suggest that traditional workouts with high volumes are less suitable for increasing performance in highly trained endurance athletes in comparison to those organized in blocks with lower volume and higher intensity [37,188-190]. For example, it has been shown that a block periodized season, reducing by 50% the volume of the previous season produces greater increases in power and speed of rowing in a group of elite rowers (which included two Olympic Champions) [188]. Similarly, it is known that extremely high intense training sessions can induce a state of acute fatigue or even overtraining producing

descensos notables en el rendimiento físico tanto en actividades de resistencia como de fuerza [63,121,128,146,162]. En definitiva, nuestros datos demuestran que los atletas que entrenaron con mayores niveles de esfuerzo percibido y mayor cantidad de kilómetros mostraron niveles mayores de cortisol libre en saliva y menores de CMJ durante toda la temporada.

Finalmente, este primer artículo de la presente Tesis Doctoral analizó los valores de CMJ, cortisol libre en saliva y carga de entrenamiento antes de la mejor (SB) y peor (SW) competición de la temporada. En concreto, antes de la SB, los niveles de CMJ fueron significativamente más altos que la media de la temporada (+8.3%), mientras que antes de la SW no hubo diferencias significativas con la media de la temporada. Estos resultados concuerdan con un estudio previo de Jiménez-Reyes y González-Badillo [25] en donde obtuvieron resultados similares con un grupo de sprinters de alto nivel a los que se midió el CMJ semanalmente durante dos temporadas consecutivas. Además, nuestros datos muestran que la semana previa a la SB tuvo unos niveles de RPE significativamente menores a la media de la temporada

significant declines in physical performance in both endurance and strength sports [63,121,128,146,162]. In conclusion, our data demonstrate that athletes who trained with higher levels of perceived exertion and most kilometers per week showed higher levels of free cortisol in saliva and lower CMJ height during the whole season.

Finally, the first article of the present PhD Thesis analyzed the values of CMJ, salivary-free cortisol and training load before the best (SB) and worst (SW) competition of the season. Specifically, before the SB, CMJ levels were significantly higher than the average of the season (+ 8.3%), whereas before the SW there were no significant differences with the average of the season. These results are consistent with a previous study by Jiménez-Reyes and González-Badillo [25] where they obtained similar results with a group of high level sprinters whose CMJ values were measured weekly for two consecutive seasons. In addition, our data show that the week before the SB had significantly lower RPE levels in comparison with the average of the season

(-3.4%), mientras que la semana previa a la SW el RPE fue significativamente mayor (+13.7%). De hecho, aunque no de manera significativa, se observó que la semana previa a la SB los atletas corrieron 11 kilómetros menos que la media semanal de la temporada. Esto concuerda con las estrategias de tapering propuestas en la literatura científica, que implican reducir notablemente el volumen de entrenamiento la semana previa a la competición con el objetivo de reducir el grado de fatiga y alcanzar un estado de forma óptimo [17,121,191-193]. De esta forma, la monitorización sistemática del CMJ y el RPE puede aportar una información útil sobre el estado de forma de los corredores de mediofondo y fondo antes de la competición.

El segundo artículo de la presente Tesis Doctoral amplía los resultados discutidos anteriormente, mostrando relaciones significativas entre la carga de entrenamiento, el cortisol libre en saliva y la producción de fuerza de los corredores de mediofondo y fondo de alto nivel estudiados. En primer lugar, en este segundo estudio se observó que los valores medios de RPE a lo largo de la temporada correlacionaron significativamente con los valores medios

(-3.4%), while before the SW the RPE was significantly higher (+ 13.7%). In fact, although not significantly, it was observed that the week before the SB athletes ran 11 kilometers less than the weekly average of the season. This is consistent with tapering strategies proposed in the literature, involving a remarkable reduction of the training volume prior to a competition in order to reduce the degree of fatigue and to achieve a state of optimal shape [17,121,191-193] week. Thus, the systematic monitoring of the CMJ and RPE can provide useful information about the shape and competitive preparedness of high-level middle and long-distance runners before the competition.

The second paper of the present PhD Thesis extends the results discussed above, showing significant relationships between training load, salivary-free cortisol and force production in the high-level middle and long-distance runners studied. First, in this second it was observed that the season average RPE values were significantly correlated to season average

de VMP, PMP y RM en media sentadilla, así como con el tiempo en el sprint de 50m, de tal forma que aquellos atletas que entrenaron con valores medios de RPE más elevados durante toda la temporada tuvieron un rendimiento inferior en dichos test de fuerza. Además, en este segundo artículo de la presente Tesis Doctoral se observó que los niveles medios de cortisol libre en saliva correlacionaron significativamente con la RM en media sentadilla ($r = -0.514$, $p < 0.05$) y el sprint de 50m ($r = 0.737$, $p < 0.001$). Recordemos que en el primer artículo de la presente Tesis Doctoral se observó que los niveles de RPE y cortisol correlacionan significativa y negativamente con el CMJ. Así, estos resultados concuerdan con los mostrados en el primer artículo y refuerzan sus conclusiones. Específicamente, el RPE se ha mostrado como la variable mejor relacionada con los niveles de producción de fuerza en el grupo de corredores de mediofondo y fondo estudiados. En este sentido, la utilización del RPE ha mostrado ser válida y fiable no sólo para los ejercicios aeróbicos, sino también para los ejercicios de levantamiento de pesas [28,29,34,114,136]. Sin embargo, hasta donde sabemos, no existe ningún estudio previo en la literatura que analice la relación entre el RPE y el rendimiento en

MPV, MPP and RM in the half-squat exercise, as well as with the 50m sprint, so that those athletes who trained with higher RPE values throughout the season underperformed in these test of strength. Moreover, in this second paper of the present PhD Thesis it was found that the season average salivary-free cortisol levels correlated significantly with half-squat RM ($r = -0.514$, $p < 0.05$) and the 50m sprint test ($r = 0.737$, $p < 0.001$). Recall that in the first paper of this PhD Thesis it was observed that the season average RPE and cortisol levels were significantly and negatively correlated with CMJ. Thus, these results are consistent with those shown in the first paper and reinforce their conclusions. Specifically, the RPE has been shown to be the most related variable with the levels of force production in the group of high-level athletes studied. In this sense, the use of RPE has been shown to be valid and reliable not only for aerobic exercise, but also for weight-lifting exercises [28,29,34,114,136]. However, to our knowledge, there are no previous studies in the literature analyzing the relationships between RPE and strength performance

la producción de fuerza en corredores de mediofondo y fondo de alto nivel.

No obstante, la principal aportación del segundo artículo de la presente Tesis Doctoral es el análisis de la evolución de la fuerza en media sentadilla y en el sprint de 50m, durante la temporada de entrenamiento y después del descanso de verano. El entrenamiento de fuerza cada vez está cobrando más importancia en los deportes de resistencia [11,14] pues ha mostrado mejorar la economía de carrera [12,44,45,47,69,71], variable considerada clave en la mejora del rendimiento en estas especialidades dado que, en esencia, su incremento implica consumir menos energía a una misma velocidad [5,14,39,66]. De esta forma, la interferencia que el entrenamiento de fuerza podría producir en el entrenamiento de resistencia, y viceversa, ha sido estudiada ampliamente con el objetivo de buscar estrategias mediante las cuales ambas capacidades pudiesen entrenarse de manera simultánea [7,48,194]. Aunque parece que el entrenamiento de resistencia y fuerza pueden interferir negativamente el uno en el otro[7], existen numerosas evidencias que demuestran efectos satisfactorios del entrenamiento concurrente de fuerza y resistencia [41,43,67,68,70,75,76,195].

in high-level middle and long-distance runners.

However, the main contribution of the second paper of this PhD Thesis is the analysis of the time-course of the half-squat force production and the 50m sprint during the training season and after the off-season break. Strength training is becoming increasingly important in endurance sports [11,14] since it has been proved to improve running economy [12,44,45,47,69,71], key variable for improving performance in these specialties because, in essence, it involves consuming less energy with the same running pace [5,14,39,66]. Thus, interference that strength training could produce on endurance training, and vice versa, has been widely studied in order to find strategies by which both capacities could be improved simultaneously [7,48,194]. Although it seems that endurance and strength training may negatively interfere with each other [7], there is abundant evidence demonstrating satisfactory effects of concurrent strength and endurance training [41,43,67,68,70,75,76,195].

Por ejemplo, Francesca-Piacentini et al. [70] realizaron un estudio con corredores bien entrenados para analizar los efectos del entrenamiento de fuerza sobre la fuerza máxima y la economía de carrera. Después de 6 semanas entrenando 2 sesiones semanales de fuerza con cargas del 85-90%RM, los corredores mejoraron significativamente su RM en press de piernas y su economía de carrera al ritmo de maratón, mientras que el grupo control, que realizó el mismo entrenamiento de resistencia sin incluir las sesiones de fuerza, no mejoró ninguna de estas variables.

Sin embargo, los atletas participantes en nuestro estudio mantuvieron sus valores de fuerza, potencia y velocidad en media sentadilla, así como el sprint de 50m, significativamente estables desde el principio hasta el final de la temporada. Es decir, no se produjo ningún aumento significativo de la capacidad de producir fuerza a lo largo de dicho periodo. De hecho, del principio al final de la temporada los atletas redujeron significativamente su Rate of Force Development (RFD), variable que representa la capacidad de producir fuerza en la unidad de tiempo y que es considerada la mejor expresión de lo que se ha venido llamando tradicionalmente

For example, Francesca Piacentini et al. [70] conducted a study with well-trained runners to analyze the effects of strength training on maximal strength and running economy. After a 6-week training program, consisting on 2 resistance training sessions per week with loads about 85-90% RM, runners significantly improved their leg-press RM and their running economy at marathon pace, while the control group, who performed the same endurance training excluding the resistance training sessions did not improve any of these variables.

However, athletes in our study maintained their values of half-squat force, power and velocity squat, as well as the 50m sprint, significantly stable from the beginning to the end of the season. That is, there was no significant increase in the ability to produce force over the period. In fact, from the beginning to the end of the season athletes significantly reduced their Rate of Force Development (RFD), a variable that represents the ability to produce force in the unit of time and which is considered the best expression of what has been called traditionally

"fuerza explosiva" [196-198]. Así, aunque varios estudios han mostrado efectos positivos del entrenamiento concurrente de fuerza y resistencia sin interferencias entre ambas capacidades, incluso con corredores bien entrenados [42,70], parece que el entrenamiento llevado a cabo por los participantes de la presente Tesis Doctoral pudo no ser lo suficientemente adecuado para permitir el incremento de su producción de fuerza. Por un lado, se ha propuesto que para garantizar mejoras tanto en la resistencia como en la fuerza, el entrenamiento de concurrente debe organizarse en bloques en los que la fuerza ocupe, en algunos momentos, cerca del 50% de los contenidos totales de trabajo [199]. Sin embargo, los atletas participantes en la presente Tesis Doctoral entrenaban 7-10 sesiones de carrera más 2 sesiones de fuerza a la semana, lo que supone una distribución aproximada de 72-28% a favor de la resistencia. Así, puede que el excesivo volumen de trabajo de resistencia respecto al de fuerza haya perjudicado el desarrollo de la última mediante el descrito fenómeno de interferencia [7,11,14]. Por otro lado, la mayoría de trabajos que han encontrado mejoras en la fuerza después de un entrenamiento concurrente de fuerza y resistencia han utilizado cargas elevadas (en torno al 80%RM) con pocas

"explosive strength" [196-198]. Thus, although several studies have shown positive effects of concurrent strength and endurance training without interference between these two capabilities, even with well-trained runners [42,70], it seems that the training undertaken by participants in the present PhD research could not be sufficiently adequate to allow an improvement on force production. First, it has been proposed that concurrent training should be organized in blocks in which the strength training occupy, sometimes, about 50% of the total training volume to ensure improvements in both strength and endurance capacities [199]. However, the athletes participating in this PhD research trained 7-10 running sessions plus 2 strength sessions per week, which is an approximate distribution of 72-28% in favor of endurance training. So, maybe the excessive endurance workload in comparison with strength training had impaired the development of the latter by the described interference phenomenon [7,11,14]. Second, most studies which have found improvements in strength after a concurrent strength and endurance training have used high loads (around 80% RM) with few

repeticiones [14,70,75,76] o ejercicios pliométricos[41,42]; ambos tipos de entrenamiento enfocados a la mejora de los factores neurales de la fuerza [10,48,57,200]. Dichos tipos de entrenamientos con pocas repeticiones y enfocados a la mejora de los factores neuromusculares de la fuerza parecen ser capaces de evitar interferencias con el entrenamiento de resistencia y se han propuesto como mucho más eficaces que los que usan múltiples repeticiones hasta el fallo [14,41,189,201]. Sin embargo, el entrenamiento de fuerza llevado a cabo por los corredores de la presente Tesis Doctoral estuvo centrado en la llamada “fuerza-resistencia”, y consistió en múltiples ejercicios con repeticiones al fallo y cargas aproximadas del 55-60%RM. En este sentido, la no mejora de la producción de fuerza a lo largo de la temporada, y el decremento significativo de la RFD a lo largo de la misma puede haberse debido a un volumen de entrenamiento de resistencia demasiado elevado respecto al de fuerza así como a la utilización de unas cargas de trabajo que no inciden especialmente en los factores neuromusculares y con múltiples repeticiones hasta el fallo; configuración que ha mostrado afectar negativamente a la potencia muscular y a la producción de fuerza en la unidad de

repetitions [14,70,75,76] or plyometric exercises [41,42]; both types of training focused to improve the neural factors of the muscular strength [10,48,57,200]. These types of workouts with low repetitions and focused on improving neuromuscular factors seem able to avoid interference with endurance training and have been proposed as more effective than those programs using multiple repetitions to failure [14,41,189,201]. However, strength training carried out by the athletes on this PhD research was focused on the "strength endurance" capacities, and consisted on multiple exercises with repetitions to failure loads and approximate 55-60% RM. In this regard, the null improvement of force production and the significant decrease of the RFD from the beginning to the end of the season may have been due to the high volume of the endurance training in comparison with the strength training, as well as for the use of training loads with repetitions to failure that does not particularly affect the neuromuscular system; configuration that has been shown to adversely affect muscle power and force production in the unit

tiempo [162,189,202,203]. Es más, se ha demostrado que un programa de entrenamiento de fuerza consistente en tan sólo 2 series de sentadilla al 80%RM al fallo por semana reduce significativamente la RFD en 4 semanas en sujetos entrenados en fuerza [203]. Sin embargo, dada la escasa investigación al respecto, son necesarios más estudios que ayuden a establecer cargas óptimas de trabajo para el trabajo de fuerza a lo largo de una temporada de entrenamiento en corredores de mediofondo y fondo de alto nivel.

Por último, tras un seguimiento durante una temporada de entrenamiento, la presente Tesis Doctoral culminó con un estudio en el Campeonato de España de Atletismo 2012-2013, celebrada en Julio y considerada la competición más importante de la temporada, pues ayuda a la concesión de becas y califica para competiciones internacionales de máximo nivel. Este último artículo amplía los resultados obtenidos en los artículos 1 y 2 de la presente Tesis Doctoral y muestra datos novedosos sobre la monitorización del grado de fatiga en corredores de mediofondo y fondo de alto nivel ante la competición más importante del año. En concreto, este último estudio mostró que los atletas tuvieron valores

of time [162,189,202,203]. Moreover, it has been shown that a resistance training program consisting in just 2 sets of squats at 80% RM to failure per week significantly reduces the RFD in 4 weeks in strength-trained subjects [203]. However, given the limited research in this regard, further studies are needed to establish optimal workloads for the strength development throughout a training season in high-level middle and long-distance runners.

Finally, after monitoring the training process during the whole season, this PhD research culminated with a study in the Spain National Track& Field Championships, held in July and considered the most important competition of the season, since it gives important economical rewards and qualify for International high-level competitions. This last paper extends the results obtained in papers 1 and 2 of the present PhD Thesis and shows new results about the monitoring of the degree of fatigue in high-level middle and long-distance runners on the most important competition of the season. Particularly, this last study shows that athletes had significantly

significativamente más altos de cortisol y más bajos de CMJ después de la competición en comparación con una medición realizada 90 minutos antes de la misma; resultados esperables que ya han sido observados previamente con distintos deportistas, incluidos corredores de maratón [105,204,205]. Además, el incremento pre-post competición del cortisol libre en saliva correlacionó significativamente con el decremento del CMJ ($r = 0.782$, $p < 0.05$), de tal manera que los atletas que perdieron más CMJ después de la carrera fueron los que vieron sus valores de cortisol más incrementados. Del mismo modo, la sensación de esfuerzo percibido de la competición (RPE 0-10) correlacionó significativamente con la pérdida de CMJ ($r = 0.762$, $p < 0.001$). En este sentido, la pérdida de CMJ ya ha mostrado previamente ser un excelente indicador del grado de fatiga neuromuscular [32,102,173,206,207]. Por ejemplo, se han demostrado correlaciones significativas muy altas ($r > 0.9$) entre la disminución de la altura del CMJ después de múltiples series de sentadilla, la pérdida de velocidad dentro de cada serie y la acumulación de lactato y amonio en sangre en sujetos físicamente activos [32]. Nuestros datos amplían el conocimiento existente en la literatura, mostrando la

higher salivary-free cortisol and lower CMJ values after the competition compared to a measurement taken 90 minutes before it; expected results that have been observed previously with other athletes, including marathon runners [105,204,205]. Moreover, the increase in pre-post competition salivary-free cortisol correlated significantly with the decrease of the CMJ ($r = 0.782$, $p < 0.05$), so that athletes who lost more CMJ after the race were those who had their cortisol values more increased. Similarly, the rate of perceived exertion after the competition (RPE 0-10) correlated significantly with the decrease of CMJ ($r = 0.762$, $p < 0.001$). In this sense, CMJ decrease has previously been shown to be an excellent indicator of the degree of neuromuscular fatigue [32,102,173,206,207]. For example, it has been observed very high significant correlations ($r > 0.9$) between the CMJ height decrease after multiple sets of squat, the decrease of velocity within each set and the accumulation of blood lactate and ammonium [32]. Our data expand the existing knowledge in the literature, showing the

idoneidad del CMJ para monitorizar el grado de fatiga de corredores de mediofondo y fondo de alto nivel tras la competición más importante del año.

Es de destacar que los corredores de distancias más largas obtuvieron incrementos de cortisol más elevados que los que corrieron distancias más cortas. Específicamente, los atletas que compitieron en la distancia de 5000m incrementaron sus niveles de cortisol en torno a un 199%, mientras que quienes compitieron en eventos de 800-1500m lo hicieron en un 37.6%. Estos resultados concuerdan con otro estudio previo en el que se observó que los corredores de ultramaratón incrementaron sus niveles de cortisol después de la competición en un 220% [163], aunque no conocemos estudios que comparen las distintas respuestas hormonales en corredores de alto nivel de distintas especialidades. A pesar de ello, no observamos diferencias en la pérdida de CMJ o el valor del RPE entre distancias. Finalmente, se observó que los atletas tuvieron valores significativamente más altos de cortisol libre en saliva y de CMJ el día de la competición en comparación con la media de las 4 semanas previas. Es más, el incremento de cortisol y CMJ respecto a sus valores medios en esa línea

suitability of the CMJ to monitor the degree of fatigue in high-level middle and long-distance runners during the most important competition of the season.

It is worth mentioning that runners competing in longer distances obtained increases of cortisol higher than those who ran shorter distances. Specifically, athletes who competed in the 5000m distance increased their cortisol levels about 199%, while those who competed in the 800-1500m events did so about 37.6%. These results are consistent with a previous study in which it was observed that ultramarathon runners increased their cortisol levels after the competition by 220% [163], although we are not aware of studies comparing different hormonal responses in high-level runners of different specialties. However we did not observe any differences in the CMJ decrease or the RPE values between the different events. Finally, we observed that the athletes had significantly higher salivary-free cortisol and CMJ levels the day of the competition compared to the average of the previous 4 weeks. Moreover, the increase in cortisol and CMJ in comparison with its baseline

base de 4 semanas correlacionaron significativa y positivamente ($r = 0.688$, $p < 0.001$). En este sentido, se sabe que las competiciones de máximo nivel pueden incrementar los niveles basales de cortisol libre en saliva [3,26] o el rendimiento físico por un aumento de los estados de ansiedad, disfrute o motivación, entre otros factores [208]. Sin embargo, como ya hemos comentado anteriormente, los factores que favorecen la relación entre los niveles de cortisol y el rendimiento neuromuscular son confusos y necesitan ser más estudiados para entender por qué en algunos casos dichas relaciones son positivas y en otros, negativas.

average values were significantly and positively correlated ($r = 0.688$, $p < 0.001$). In this regard, it is known that high level competitions can increase the basal levels of salivary-free cortisol [3,26] or physical performance by increasing anxiety states, enjoyment or motivation, among other factors [208]. However, as mentioned above, the factors that favor the relationship between cortisol levels and neuromuscular performance are unclear and need to be studied to understand why in some cases these relationships are positive and in others cases, negative.

Limitaciones del estudio

A pesar de que la presente Tesis Doctoral muestra novedosas relaciones entre los valores de carga de entrenamiento, cortisol libre en saliva, CMJ o producción de fuerza a lo largo de toda una temporada competitiva en corredores de mediofondo y fondo de alto nivel, este estudio no está exento de limitaciones que merecen ser comentadas. En primer lugar, el tamaño muestral de la presente Tesis Doctoral no ha sido muy grande y, en consecuencia, no se han podido establecer comparaciones en los resultados obtenidos entre distintos subgrupos. Por ejemplo, sería muy interesante conocer si hombres y mujeres, especialistas en distintas distancias de menor a mayor longitud tienen respuestas específicas y diferenciadas al resto. En nuestro caso, contamos con sólo 3 mujeres y un total de 15 corredores entre los que se incluyen especialistas desde 800m hasta 5000m pertenecientes a un mismo grupo de entrenamiento, por lo que los datos se han analizado globalmente sin la posibilidad de crear subgrupos con tamaños muestrales suficientes. Otra de las principales limitaciones de este estudio ha sido la financiación del mismo.

Study's limitations

Altough this PhD Thesis shows novel relationships between training load, salivary-free cortisol, CMJ or force production over an entire season in high-level middle and long-distance runners, this study has some limitations that deserve to be discussed. First, the sample size of the present PhD research is not very large and, therefore, it was not possible to make comparisons between different subgroups. For example, it would be interesting to know whether men and women and specialists in different distances from lower to higher distances would show the same results. In our case, we had only 3 women and a total of 15 runners, specialists from 800m to 5000m within the same training group, so the data were analyzed globally without the ability to create subgroups with sufficient sample sizes. Another major limitation of this study was its financing.

Dado que la presente Tesis Doctoral no ha estado financiada por ninguna institución pública o privada, no hemos podido realizar todos los test que en un principio hubiésemos considerado ideales. Específicamente, dado nuestro interés por analizar la capacidad de producir fuerza de los participantes y su relación con las cargas de entrenamiento, hubiese sido muy interesante poder haber medido la economía de carrera, variable clave para el rendimiento de estos deportistas y que se sabe que puede incrementarse notablemente con el entrenamiento de fuerza [5,11,47,71]. Por último, la propia naturaleza de los deportistas de alto nivel, en muchas ocasiones reacios a cambios en sus dinámicas de entrenamiento, han impedido analizar las cargas de entrenamiento de una manera más individualizada mediante el uso de los llamados training impulses (TRIMPS). Aunque existen diferentes fórmulas para calcularlos, los TRIMPS se basan en la medición diaria de la frecuencia cardíaca durante la sesión para después multiplicarla por el tiempo o el volumen de entrenamiento. De esta forma, la carga de entrenamiento medida con los TRIMPS se considera más adecuada porque aporta información individual de la carga interna del deportista [4,18,19,133].

Since this PhD Thesis has not been funded by any public or private institution, we could not perform all the tests that we had initially considered. Specifically, given our interest in analyzing the ability to produce force of the athletes and its relationship with training loads, it would have been very interesting to have measured running economy, a key variable for the performance of these athletes which has been probed to be incremented with strength training [5,11,47,71]. Finally, the own characteristics of high-level athletes, not very proactive to changes in their training processes, have prevented the measurement of the training load in a more individualized way using the training impulses (TRIMPS). Although there are different equations for calculating the TRIMPS, most of them are based on daily measurement of heart rate during the session and then multiply it by training time or volume. Thus, the training load measured with TRIMPS is more appropriate because it provides individual information on the internal load of the athlete [4,18,19,133].

Sin embargo, los atletas participantes en la presente Tesis Doctoral nunca entrenan con pulsómetro, e intentar que lo hicieran durante sus múltiples sesiones semanales a lo largo de toda una temporada no fue posible. Aunque la utilización del RPE como indicador de carga interna ha mostrado ser altamente fiable y estar muy relacionado con otras variables fisiológicas [131,132], la medición diaria de la frecuencia cardíaca habría aportado datos de gran relevancia para el análisis de las cargas de entrenamiento.

Así, son necesarios más estudios, con muestras más amplias y con mediciones más completas de sus cargas de entrenamiento para comprobar si los corredores de mediofondo y fondo de alto nivel de distintas especialidades y géneros responden de manera especial a una temporada entera de preparación, lo cual ayudaría a individualizar el proceso de entrenamiento y a optimizar las estrategias de monitorización del mismo.

Por último, cabe mencionar que las correlaciones obtenidas en la presente Tesis Doctoral no pueden ser generalizadas por la propia limitación estadística que supone, como se ha comentado anteriormente, contar con una muestra tan reducida. Si bien en la

However, the athletes participating in this PhD research never train with heart rate monitor, and try to do so during his multiple weekly sessions over an entire season was not possible. Although using RPE as an indicator of internal training load has shown to be highly reliable and related to other physiological variables [131,132], the daily measurement of the heart rate could have added relevant data for the analysis of the training loads.

Thus, further studies with larger samples and more complete measurements of their training loads are necessary to verify if high-level middle and long-distance runners, of different genders and specialities have specific responds to an entire training season, which could help to individualize the training process and to optimize its monitoring strategies.

Finally, it worth mentioning that the correlations obtained in the present PhD Thesis can't be generalized because of the previously mentioned limitation of this study: its small sample size.

presente Tesis Doctoral tanto las correlaciones significativas como los tamaños del efecto y los intervalos de confianza permiten establecer unas conclusiones firmes sobre la evolución y las relaciones entre las variables estudiadas en un grupo de corredores de mediofondo y fondo de alto nivel, estos datos deben tomarse con cautela, siendo necesarios más estudios que confirmen los resultados que aquí se exponen.

Although in the present PhD. Thesis the significant correlations, effects sizes and confidence intervals allows us to establish several conclusions about the evolution and correlations between the variables in the group of elite runner studied, this data must be taken carefully, being necessary more studies that confirm the results showed in this work.

Perspectivas de futuro

En coherencia con las principales limitaciones metodológicas de la presente Tesis Doctoral descritas anteriormente, el autor de la misma considera que pueden existir, al menos, tres vías de desarrollo mediante las cuales el conocimiento sobre la monitorización de los procesos de entrenamiento de los atletas de alto nivel puede verse ampliado sustancialmente en el futuro. A continuación, dichas perspectivas de futuro van a describirse brevemente.

Prospects

In coherence with the main methodological limitations present on this PhD Thesis, the author considers that, at least, there are 3 future research lines through which the knowledge about the monitoring of the training process of elite athletes could be substantially extended. Below these prospects are briefly described.

Ampliación de la muestra

Por la propia naturaleza de los deportistas de alto nivel, de características excepcionales, es muy complicado encontrar sujetos que puedan participar en investigaciones de este tipo, especialmente si consisten en seguimientos tan cercanos del proceso de entrenamiento, con mediciones diarias y semanales de diversas variables psico-fisiológicas durante toda una temporada de entrenamiento. Así, es difícil contar con un grupo formado por este tipo de sujetos, situados entre los mejores del territorio nacional en su especialidad. Además, los propios entrenadores y atletas de alto nivel, según nuestra experiencia, tienden a ser reacios a mostrar sus planes de entrenamiento y a colaborar en tareas de investigación, lo cual complica aún más la selección de participantes.

Por todo ello, las dificultades en el reclutamiento de la muestra nos han impedido realizar análisis comparativos entre diversos géneros o diversas especialidades que, con un mayor número de sujetos, podrían haberse estudiado. De esta forma, un paso lógico en el horizonte investigador es conseguir un mayor número de participantes de ambos géneros y diversas especialidades

Higher sample size

The exceptional characteristics of elite athletes makes very difficult to find subjects for scientific research, specially if the project consist on long-term, daily monitoring of psycho-physiological variables. Thus, it is not easy to have a sample formed by this kind of subjects, some of the Spain bests on his/her specialities. Also, elite athletes and coaches themselves are unwilling to show their training programs and to collaborate on research activities, which make the sample recruitment harder.

Therefore, the difficulties on the subjects recruitment have had prevented us to realize comparative analysis between genders or running specialities (i.e., event distance) that could have been studied with larger sample sizes. Thus, a logical step forward for future research is to recruit more elite athletes of both genders and form different specialities

solicitando colaboración a las federaciones autonómicas y nacionales. Por ejemplo, un estudio similar al que describimos en el Artículo 3 de la presente Tesis Doctoral, en el que se analizaron los efectos que el Campeonato de España produce en los niveles hormonales y neuromusculares de los atletas podría ampliarse sustancialmente si se contase con la Real Federación Española de Atletismo y pudiésemos medir variables como el cortisol, el lactato o el salto vertical a todos los finalistas de todas las disciplinas de mediofondo y fondo de dicha competición. De esta forma, una mayor muestra permitiría avanzar en el conocimiento de las relaciones entre la carga de entrenamiento, el grado de fatiga y el rendimiento en atletas hombres y mujeres de alto nivel de distintas distancias.

by collaborating with autonomic and nationals federations. For example, a study similar to the Paper 3 of the present PhD Thesis, in which hormonal and neuromuscular responses to the Spanish National Track & Field Championships were analyzed could be substantially extended if the Spanish National Track & Field Federation could allow us to measure variables such as salivary-free cortisol, the CMJ or blood lactate to every single finalist in every single event of the championship. Thereby, a bigger sample size could allow to advance in the knowledge of the relationships between training load, fatigue and performance in male and female elite athletes from different specialities.

Análisis de la economía de carrera

Las otras limitaciones principales que se describieron anteriormente hacían relación a la complejidad que existe actualmente para medir diversas variables relacionadas con el estado interno de los deportistas, ya sea por deficiencias tecnológicas-metodológicas o por problemas de financiación. En nuestro caso, no pudimos medir la economía de carrera por problemas de financiación, ya que la medición de la economía de carrera requiere un instrumental de laboratorio muy específico del que no se pudo disponer para la presente Tesis Doctoral.

La economía de carrera está cobrando una gran popularidad en la literatura científica porque se sabe que es uno de los mejores indicadores del nivel de rendimiento de los atletas de élite [5,11,47,71]. Así, habiéndose encontrado en la presente Tesis Doctoral notables relaciones entre los niveles de producción de fuerza, la carga de entrenamiento y el grado de fatiga, y sabiendo que el entrenamiento de fuerza es capaz de mejorar sustancialmente la economía de carrera [11,71], un siguiente paso en el horizonte investigador sería estudiar la evolución de la economía de carrera y sus

Analysis of running economy

The other main limitations described above highlighted the difficulty that exists when measuring certain variables related to the athlete's internal training load, both for funding or technological issues. In our case, we couldn't measure running economy for lack of funding, since the measurement of running economy requires very specific laboratory instrumental that we couldn't afford for the present PhD Thesis.

Running economy is becoming very popular on the scientific literature because it has been probed to be one of the best performance indicators of elite athletes [5,11,47,71]. Taking into account that, first, the present PhD Thesis have found remarkable relationships between force production levels and training load or fatigue, and second, knowing that strength training can substantially increase running economy [11,71], a logical next step could be to study the time-course of running economy and

relaciones a lo largo de toda una temporada con otras variables asociadas a la producción de fuerza como el salto vertical, o a los niveles de carga de entrenamiento o del grado de fatiga, lo cual podría ampliar sustancialmente el conocimiento sobre la importancia de la monitorización de la fuerza y la economía de carrera en corredores de alto nivel.

its relationships with other variables, such as force production, training load or the degree of fatigue throughout a training season. This could extend significantly the knowledge about the importance of monitoring strength levels and running economy in elite runners.

Monitorización sistemática de la carga interna

La monitorización de la carga interna de entrenamiento, esto es, el efecto interno e individual que un determinado estímulo produce al deportista es la manera más precisa y certera de controlar las adaptaciones al entrenamiento [1,4,17,114]. Sin embargo, la tecnología aún requiere de métodos poco amigables con el deportista para el registro de la carga interna que un entrenamiento supone, dificultando mucho su uso diario durante períodos de tiempo prolongados. Un ejemplo muy común son los medidores de frecuencia cardíaca. Si bien habría sido de enorme interés conocer la frecuencia cardíaca de los atletas participantes en la presente Tesis Doctoral diariamente durante toda la temporada de entrenamiento, a efectos prácticos dicha medición no pudo realizarse a pesar de disponer de los pulsómetros necesarios. Los atletas suelen encontrar incómoda la banda que se coloca en el pecho para registrar la frecuencia cardíaca, y su uso diario durante las más de 40 semanas de estudio no fue posible. Sin embargo, nuevas tecnologías que podrían facilitar enormemente la monitorización sistemática de la carga interna de una manera no invasiva y cómoda para el

Systematic monitoring of the internal training load

Monitoring internal training load (i.e., the internal, individual response that a specific stimuli produces to the athlete) is the better and more accurate way to control the adaptations to training [1,4,17,114]. However, current technology still requires non-friendly methods to register athlete's internal training load, making difficult its use on a daily basis for prolonged training periods. Heart-rate monitors are a typical example. Although it would have been very interesting for the present PhD Thesis to know the daily heart rate of the athletes during their training throughout the entire season, it could not be measured (despite having enough heart rate monitors in our lab). This is because elite athletes often find annoying the chest strap of the current heart rate monitors, and using them every single day for more than 40 weeks was not possible. However, new technologies that allows to monitor internal training load in a user-friendly, comfortable way

deportista empiezan a aparecer en el mercado. Por ejemplo, están comenzando a comercializarse pulseras con sensores ópticos que permiten medir la frecuencia cardíaca directamente en la muñeca sin necesidad de colocar una banda en el pecho de los deportistas por unos 100€, bastante menos que los pulsómetros convencionales hace unos pocos años. Dichos sensores llamados *weareables*, es decir, que pueden instalarse en prendas de vestir y accesorios de moda, permitirían medir la calidad del sueño, el índice de sudoración, la temperatura corporal o incluso el lactato sanguíneo en un futuro inmediato de acuerdo a sus diversos fabricantes.

El autor de la presente Tesis Doctoral encuentra fascinante esta inminente revolución en la tecnología del deporte, pues cada vez va a ser más fácil y asequible monitorizar más variables internas del deportista de manera amigable e inocua para los atletas, lo cual ayudará enormemente a conocer el grado de fatiga de los deportistas y a optimizar sus procesos de preparación y recuperación. De esta forma, en el futuro sería muy interesante monitorizar diariamente diversas variables relacionadas con la carga interna y el grado de fatiga de los corredores como la

are rising. For example, some manufacturers are starting to release wristband with built-in optical sensors that allows to measure heart rate directly on the wrist with no chest straps at a retail price about 100€, much less than many traditional heart rate monitors just a few years ago. Those sensors, called weareables (i.e., which can be installed on clothes and fashion accessories) could measure sleep quality, sweating rates, body temperature or even blood lactate thresholds in the nearest future according to the manufacturers.

The author of the present PhD Thesis finds fascinating this imminent sport technology revolution, since internal training load would become easier and much more affordable, which could help greatly to know the level of fatigue of the athletes and to optimize the training and recovery processes. Thus, in the future it would be really interesting to monitor in a daily basis some variables related to fatigue or training load such as

frecuencia cardíaca y la calidad del sueño utilizando estos nuevos dispositivos que comienzan a aparecer en el mercado. Además, dado que los procesos de entrenamiento y competición de alto nivel pueden tener un impacto emocional grande sobre el rendimiento de los deportistas (y viceversa), sería interesante estudiar las relaciones que pudieran existir entre el rendimiento puramente fisiológico y diversas variables psicológicas como la ansiedad precompetitiva o los niveles de motivación. Así, podrían recolectarse datos fisiológicos y psicológicos relevantes sobre el estado de forma y los niveles de recuperación de los atletas de alto nivel de manera sistemática y prolongada sin que ello interfiera en sus procesos de entrenamiento, lo cual podría ayudar a optimizar su preparación y sus niveles de rendimiento.

hear rate or sleep quality using this new weareable devices. Also, taking into account that training process and competitive events may have a significant emotional impact on the performance of the athletes (and vice-versa), it would be interesting to study the relationships that could exist between the physiological performance and some psychological variables such as pre-competitive anxiety or motivation status. This way, relevant physiological and psychological data about the fitness and recovery states of the athletes could be collected in a systematic way for a long period, which could help optimizing their training process and, therefore, their performance.

Conclusiones y aplicaciones prácticas

Conclusions and practical applications



Conclusiones

i. La carga de entrenamiento, los niveles de cortisol libre en saliva y el CMJ medidos a lo largo de una temporada de entrenamiento están relacionados entre sí. Específicamente, los atletas que entrenaron con menores sensaciones de esfuerzo y menores kilómetros semanales tuvieron niveles de cortisol libre en saliva más bajos y valores de CMJ más altos. De hecho, antes de la mejor competición de

Conclusions

i. Training load, salivary-free cortisol and CMJ measured over a training season are interrelated. Specifically, athletes who trained with lower perceived exertion values and weekly kilometers had lower salivary-free cortisol and higher CMJ values. In fact, before the best competition

la temporada, los valores de CMJ son significativamente mayores y los de RPE menores a la media de la temporada. Así, la monitorización sistemática del CMJ y el RPE puede aportar información práctica para el seguimiento del entrenamiento de corredores de mediofondo y fondo de alto nivel de una manera no invasiva y económica.

ii. La producción de fuerza de los atletas, medida mediante el rendimiento en media sentadilla y el sprint de 50m está relacionada con el cortisol libre en saliva, la zona de entrenamiento y, especialmente, con el RPE. En concreto, los atletas que entrenaron con niveles más bajos de RPE obtuvieron rendimientos superiores en el test de fuerza en media sentadilla y en el sprint de 50m. La monitorización del RPE puede ser de utilidad en el control del entrenamiento de fuerza de los corredores de mediofondo y fondo de alto nivel.

iii. El entrenamiento de fuerza llevado a cabo, con muchas repeticiones (15-20RM) y sólo 1-2 sesiones por semana puede no ser suficiente para mejorar la fuerza de los corredores de mediofondo y fondo de alto nivel.

of the season, CMJ values were significantly higher and RPE values were significantly lower than the season average. Thus, the systematic monitoring of CMJ and RPE can provide useful information for the training process of high-level middle and long-distance runners in a non-invasive and inexpensive way.

ii. Force production of the athletes, as measured by performance on the half-squat and the 50m sprint test is related to salivary-free cortisol, the training zone and especially the RPE. Specifically, athletes who trained with lower levels of RPE obtained higher performance in both the half-squat and the 50m sprint test. Monitoring RPE may be useful for controlling the strength training in high-level middle and long-distance runners.

iii. The strength training conducted by the athletes on this PhD research, with many repetitions until failure (15-20RM) and only 1-2 sessions per week may not be enough to improve the strength of high-level middle and long-distance runners.

iv. El decremento post-competición del CMJ se correlaciona significativamente con el incremento de cortisol libre en saliva y con los valores de RPE en corredores de mediofondo y fondo de alto nivel. Por tanto, el CMJ es una herramienta útil, de fácil medición y no invasiva para evaluar el grado de fatiga de los atletas ante una competición de máximo nivel.

iv. The post-competition CMJ decrease is significantly correlated with the increase of salivary-free cortisol and the RPE values in high-level middle and long-distance runners. Therefore, the CMJ is a useful, easy to measure and non-invasive tool for assessing the degree of fatigue of such athletes on a high-level competition.

Aplicaciones prácticas

i. Técnicos y entrenadores de corredores pueden monitorizar el entrenamiento de una manera sencilla, no invasiva y económica registrando el RPE diario y el valor de CMJ una vez a la semana. El análisis de los valores semanales de dichas variables a lo largo de la temporada puede aportar información útil sobre el grado de fatiga de los deportistas. Específicamente, si el CMJ permanece disminuido y el RPE aumentado durante un periodo de tiempo prolongado, técnicos y entrenadores pueden considerar ajustar sus cargas de entrenamiento, especialmente si hay una competición cercana.

ii. Del mismo modo, la monitorización del RPE puede aportar información valiosa

Practical applications

i. Running coaches can monitor training process on a simple, non-invasive and economical way by recording the RPE every day and the CMJ height once a week. The analysis of the weekly values of these variables throughout the season can provide useful information about the degree of fatigue of the athletes. Specifically, if the CMJ remains decreased and the RPE increased during an extended period of time, coaches could consider adjusting their training loads, especially if there is a competition soon.

ii. Similarly, monitoring RPE could provide valuable information

a los entrenadores sobre la capacidad de producir fuerza de los deportistas. Valores sistemáticamente elevados de RPE pueden favorecer unos bajos niveles de fuerza.

iii. Probablemente, los corredores de mediofondo y fondo de alto nivel vean sus niveles de fuerza mejorar en mayor medida usando cargas elevadas de trabajo (en torno al 80%RM) y/o evitando las repeticiones al fallo, incidiendo así en los factores neurales de la producción de fuerza.

iv. El análisis de la pérdida de CMJ entre antes y después de la competición permite tener una idea del grado de esfuerzo que la carrera le ha supuesto al deportista. Decrementos muy elevados pueden indicar una intensidad de carrera máxima, mientras que decrementos muy bajos pueden significar que el deportista no se ha esforzado totalmente.

to coaches about the ability of the athletes to produce force. Consistently high levels of RPE could lead to lower strength performance.

iii. Probably, high-level middle and long-distance runners could increase their strength further using high workloads (around 80% RM) and/or avoiding repetitions to failure, thereby affecting the neural factors of the force production.

iv. The analysis of the CMJ decrease between before and after the competition provides an idea about the degree of effort that the race has produced to the athlete. Very high decreases could indicate a maximum effort, while very low decreases could mean that the athlete has not fully tried.

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Apéndices *Appendices*

Relationships between Training Load, Salivary Cortisol Responses and Performance during Season Training in Middle and Long Distance Runners

Carlos Balsalobre-Fernández*, Carlos M^a Tejero-González, Juan del Campo-Vecino

Department of Physical Education, Sport and Human Movement, Autonomous University of Madrid, Madrid, Spain

Abstract

Purpose: Monitoring training from a multifactorial point of view is of great importance in elite endurance athletes. This study aims to analyze the relationships between indicators of training load, hormonal status and neuromuscular performance, and to compare these values with competition performance, in elite middle and long-distance runners.

Method: Fifteen elite middle and long-distance runners (12 men, 3 women; age = 26.3 ± 5.1 yrs) were measured for training volume, training zone and session rate of perceived exertion (RPE) (daily), countermovement jump (CMJ) and salivary free cortisol (weekly) for 39 weeks (i.e., the whole season). Competition performance was also observed throughout the study, registering the season best and worst competitions.

Results: Season average salivary free cortisol concentrations correlate significantly with CMJ ($r = -0.777$) and RPE ($r = 0.551$). Also, weekly averages of CMJ significantly correlates with RPE ($r = -0.426$), distance run ($r = -0.593$, $p < 0.001$) and training zone ($r = 0.437$, $p < 0.05$). Finally, it was found that the CMJ (+8.5%, $g = 0.65$) and the RPE (-17.6%, $g = 0.94$) measured the week before the best competition performance of the season were significantly different compared with the measurement conducted the week before the season's worst competition performance.

Conclusions: Monitoring weekly measurements of CMJ and RPE could be recommended to control training process of such athletes in a non-invasive, field-based, systematic way.

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* Email: carlos.balsalobre@uam.es

Introduction

Although training volume is not directly related to performance of elite endurance athletes [1–3], it seems clear that such athletes need to train several hours per week during their training cycle to increase their performance [4–6]. Specifically, elite distance runners may run a lot of km throughout the season, with weekly amounts totaling up to 230 km or more in the case of marathon runners [7]. Thus, monitoring the training process of such athletes is essential in order to observe their adaptation to training load and to avoid overtraining syndrome [8–10]. Although the assessment of physiological parameters such as maximal oxygen uptake or blood cell count is of great importance in endurance sports [11,12], their invasive, laboratory-based nature complicate regular measurement during daily training. Therefore, the use of some indicators that could, systematically and without disturbing the athletes, facilitate in-the-field monitoring of the training processes required.

The most common variable used on a daily basis to monitor the training process in running is the training load [9]. Specifically,

training volume, intensity and session-RPE are the most used indicators of the training load because they can be assessed every day without disturbing the athletes and have shown significant relationships with performance or fatigue [13,14]. For example, Esteve-Lanao et al. [13] recorded training volume and intensity of sub-elite cross-country runners for 6 months, discovering that the time expended training at low intensities (below the ventilator threshold) was significantly related to performance in a cross-country competition. Similarly, Garcin et al. [14] measured session-RPE in 8 young, elite middle-distance runners for 8 weeks, proving that this indicator of training load was able to detect states of overreaching. Meanwhile, the measurement of the vertical jump score as an indicator of neuromuscular performance has been used to assess fatigue in different kinds of athletes [15–17]. For example, it has been shown that the decrease in the countermovement jump (CMJ) score after a set of full-squats performed until failure correlates highly with blood lactate concentrations ($r = 0.97$, $p < 0.001$) [17]. With respect to distance runners, it has been observed that a marathon competition significantly impairs the height reached in the CMJ [18]. Finally, the measurement of salivary free

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cortisol (hormone related with fatigue and stress) is commonly used to monitor the effects of training in several sports, due to its non-invasive, field-based nature [19,20]. Moreover, it seems that cortisol levels are related to neuromuscular performance in well-trained strength athletes [21,22]. For example, it has been demonstrated that changes in salivary free cortisol levels after 15 weeks of training are related to changes in the power clean mean power production over the same period in young elite wrestlers [23]. However, as far as we know, the relationship between salivary free cortisol levels and neuromuscular performance has not been studied on high-level middle and long-distance runners throughout a whole season.

Thus, although the measurement of the training load, salivary free cortisol or CMJ are very common to monitor training process in different kinds of athletes [7,24,25], any relationships between such variables in high-level distance runners, as well as their impact on the performance of such athletes, is, as far as we know, unknown. Therefore, the objectives of this investigation are: (1) to disclose the relationships between training load (measured using daily km run totals, training zone and session-RPE), salivary free cortisol and CMJ scores throughout a whole season in elite middle and long-distance runners; and (2) to compare the values of the study variables measured just before the season-best competition performance with the values measured just before the season-worst competition performance. As such, and according to the above, our study hypotheses are that: (a) weekly values of training load, salivary free cortisol and CMJ measured throughout the season are significantly related; and (b) the values of these variables measured just before the season-best competition performance are significantly different compared with those measured just before the season-worst competition performance.

Materials and Methods

Subjects

The participants in this study were 15 high-level middle and long-distance runners from the High Performance Sports Center Madrid (12 men, 3 women; age = 26.3 ± 5.1 yrs), with personal bests in outdoor 1500-metres between 3:38–3:58 min. (men) and 4:12–4:23 min. (women). See Table 1 for more details.

Ethics statement

The study protocol complied with the Declaration of Helsinki for Human Experimentation and was approved by the ethics committee at the Autonomous University of Madrid (approval number CEI-45 889). Written informed consent was obtained from each subject before participation.

Design

Athletes were assessed for CMJ score, salivary free cortisol levels and training load throughout a whole season (October–July, 39 weeks). CMJ and cortisol were measured once a week, while training load, assessed by session rate of perceived exertion (session-RPE), km run and training zone were measured daily. Competition performance was observed throughout the whole season, registering the season best (SB) and worst (SW) results (i.e., fastest and slowest times in competitions). Correlations between the variables evaluated in this investigation and differences in CMJ, cortisol and training load just before the SB and SW events were then analyzed. See Figure 1 for more information about the training load variation throughout the season.

Table 1. Characteristics of the participants (average \pm SD).

	Age (yrs.)	Height (cm)	Weight (kg)	PB in outdoor 1500 m (min:s)	PB in urban 10 km (min:s)	Average CMJ (cm)	Average Session-RPE (0-10)	Average weekly run	Average weekly km	Average training zone	Average salivary free cortisol (ng/mL)
Men	25.7 \pm 5.4 ^N	1.79 \pm 0.04 ^N	63.9 \pm 3.1 ^N	3:48 \pm 0.6 ^N	30:33 \pm 0:43 ^N	30.3 \pm 4.8 ^N	5.7 \pm 0.4 ^N	85.4 \pm 5.8 ^N	1.8 \pm 0.06 ^N	11.9 \pm 2.3 ^N	
Women	29.0 \pm 2.0 ^N	1.67 \pm 0.05 ^N	52.0 \pm 3.6 ^N	4:18 \pm 0.5 ^N	34:50 \pm 1:32 ^N	27.9 \pm 1.4 ^N	6.1 \pm 0.3 ^N	83.2 \pm 7.0 ^N	1.8 \pm 0.5 ^N	12.4 \pm 2.1 ^N	

^N = Normally distributed variable (Kolmogorov-Smirnov test, p>0.05). Abbreviations: PB = personal best; CMJ = countermovement jump; Session-RPE = session rate of perceived exertion.
Note: Training zones ranges from 1-3 according to session average running pace. Zone 1 = 3:45-3:10 min/km; Zone 2 = 3:10-2:50 min/km; Zone 3 = 2:50 min/km to full sprint.
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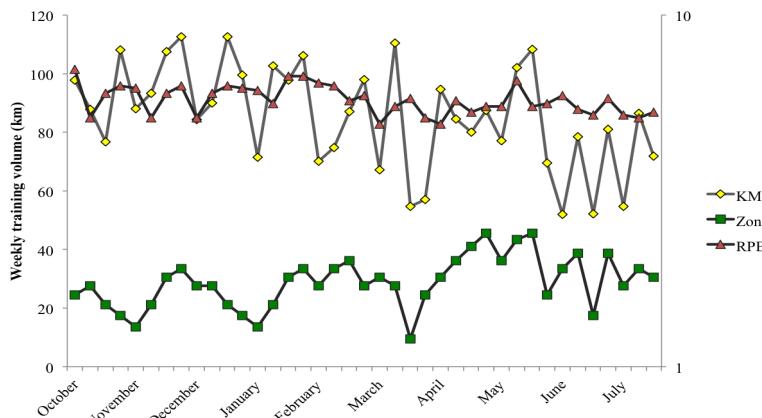


Figure 1. Training load variation throughout the whole season. Weekly training volume, training zone and session-RPE are represented. Training volume is represented on the left Y-axis (in km.), while training zone and session-RPE are represented on the right Y-axis with a logarithmic scale. Abbreviations: KM = weekly average km run; Zone = weekly average training zone; RPE = weekly average session-RPE.

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Methodology

Training load. Training load was measured daily throughout the whole season using daily session-RPE, km run and training zone parameters. Session-RPE was assessed after each training session using the Borg 0–10 scale by asking, “How hard was the training session, with 0 being very, very light and 10 extremely heavy?”. Kilometres run and training zone were recorded using the coach's endurance training programmes designed for each athlete. When an athlete couldn't fulfil his or her training programme, the km run and training zone values of the what the athlete did complete were recorded. Every training session was classified in one of 3 training zones according to the characteristics of the principle part of the session: Zone 1 included long-distance continuous training, or interval training with long sets (4–6 km), at paces of between 3:45–3:10 min/km; Zone 2 included middle-distance interval training (sets of 1–3 km) at paces between 3:10–2:50 min/km; and Zone 3 included short-distance and sprint interval training (sets of 200–600 m) at paces ranging from 2:50 min/km to full sprint.

Salivary-free cortisol. To establish the basal cortisol level (in ng/mL), athletes collected a saliva sample immediately after they woke up (i.e., 1–2 min after waking up), with an empty stomach, once a week throughout the whole season using Salivette tubes (Sarstedt, Germany). Athletes chewed the cotton inside the Salivette tube for 60 seconds after they rinsed their mouth with water, then they stored the sample at -20°C for 1 hour before subsequently bringing it to the laboratory for analysis. All measurements were performed on the same day of the week, at the same time and under the same environmental conditions. All the subjects woke up almost at the same time of the day (8:30–9 a.m.) since they lived in the same area and trained together. The samples were then stored at -20°C according to the manufacturer's instructions. All samples were analyzed at the Biochemical Laboratory of the Polytechnic University of Madrid (Official Lab. Number 242 in the Region of Madrid) using Free Cortisol in Saliva ELISA Assay kits (Demeditec Diagnostics, Germany). The coefficient of variation (CV) of the measurements was CV = 4.3–5.6%.

CMJ. The CMJ scores were measured once a week throughout the whole season, on the same day that saliva samples were collected and just before beginning the training session. An

Optojump infrared (IR) platform (Microgate, Italy) was used for the assessment. The CMJ was performed with hands on hips, knees straight in the flight phase while trying to jump as high as possible. All measurements were taken on the same day of the week, at the same time and under the same spatial and environmental conditions. The average of 3 attempts was recorded. The reliability of the measurements was calculated using the intraclass correlation coefficient (ICC = 0.979–0.990, $p < 0.001$).

Statistical analysis

To analyze the relationship between the variables, we used the Pearson correlation coefficient, unilateral contrast. For the comparison of means, we used the paired samples t-test. For the calculation of the effect size (ES), we used the Hedge's g. Effects sizes below 0.5 were considerate *low*, and ES between 0.5–1.0 were considerate *moderate to high* [26]. The level of significance was set at 0.05. All calculations were performed using IBM SPSS Statistics 22 software (IBM Co., USA).

Results

Significant correlations were found between season average CMJ and cortisol ($r = -0.777$, $p < 0.001$), CMJ and session-RPE ($r = -0.489$, $p = 0.049$) and session-RPE and cortisol ($r = 0.551$, $p = 0.025$) values. Analysis of the average weekly values of the variables throughout the whole season showed that CMJ scores correlate significantly with session-RPE ($r = -0.426$, $p = 0.012$), cortisol ($r = 0.556$, $p < 0.001$), km run ($r = -0.593$, $p < 0.001$) and training zone ($r = 0.437$, $p = 0.007$). Also, km run correlates significantly with session-RPE ($r = 0.444$, $p = 0.009$) and cortisol levels ($r = -0.366$, $p = 0.017$). See Table 2 for more details.

Comparing the values for the variables measured the week before the season-best (SB) and season-worst (SW) competition performances, it was found that the CMJ scores prior to the SB was significantly higher than the CMJ score prior to the SW (+ 8.5%, $g = 0.65$, $p < 0.001$). The session-RPE for the week before the SB was significantly lower than the session-RPE for the week before the SW (-17.6% , $g = 0.94$, $p = 0.022$). There were no significant differences between salivary free cortisol, km run or

Table 2. Pearson correlation coefficient (r) between study variables.

	Session-RPE	Cortisol	Km run	Training zone
	Season average	Weekly average	Season average	Weekly average
CMJ	-0.489*	-0.426*	-0.777**	0.556**
Session-RPE	-	-	0.551*	0.444*
Cortisol	-	-	-0.051	-0.366
Km run	-	-	-	-0.599*

Season average: correlations between average variables for the group throughout the whole season; Weekly average: correlations between average variables of the group for every week of the season. CMJ = countermovement jump score; Session-RPE = rate of perceived exertion of the training session; km run = total weekly km run.

* $p<0.05$;
** $p<0.001$.

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training zone values measured before SB and SW. See Table 3 for more details.

Discussion

The results of our study have revealed that noteworthy relationships exist between salivary free cortisol and CMJ scores assessed throughout a whole season in elite middle and long-distance runners. Also, moderate relationships between session-RPE and salivary-free cortisol were found. Firstly, our data demonstrates a significant trend in which athletes with higher [average] cortisol levels measured throughout the season were those with lower CMJ scores. It worth to mention that females and males salivary free cortisol were equivalent throughout the season, despite some studies have reported hormonal differences between sexes [27,28]. It has previously been demonstrated that post-exercise blood lactate and ammonia concentrations are negatively and significantly related to the height jumped in the CMJ performed just after an intensive exercise session, so greater CMJ decreases correspond to a higher level in such physiological markers [17]. In highly-trained strength athletes, it was observed that salivary cortisol is negatively and significantly related to neuromuscular performance [14,22]. For example, Kraemer et al. [22] studied the changes on cortisol and performance of a group of highly-trained soccer players throughout a season, and they showed that salivary cortisol levels measured before training have a significant correlation with the vertical jump height scores recorded on the same day ($r = -0.59$, $p < 0.05$). That study concludes that athletes starting the season with elevated cortisol values may experience significant reductions on performance during the season. Our study expands the knowledge in this respect, demonstrating that subjects with higher long-term salivary free cortisol levels significantly tend to be those with lower CMJ scores throughout the season. However, when correlations between weekly average cortisol and CMJ values were analyzed, a significant trend was observed in which the weeks with higher salivary free concentrations were those in which higher CMJ scores were recorded. Thus, despite athletes with higher [average] cortisol levels throughout the season had significantly lower CMJ [average] values, it seems that weeks with higher cortisol concentrations produce a potentiation of CMJ performance. Although some investigations have studied the relationships between salivary cortisol concentrations and force production [23] or vertical jump [21], they used strength-related athletes and measured the variables less frequently (6 times during a season). However, we are not aware of studies which analyze the relationship between weekly salivary free cortisol concentrations and CMJ height measurements throughout a whole season in elite middle and long-distance runners. Further research is needed to clarify the nature of the relationship between salivary cortisol concentrations and CMJ performance in elite middle and long-distance runners.

Furthermore, training load was also shown to correlate significantly with salivary cortisol levels and CMJ scores. Specifically, weekly values for session-RPE, km run and training zone correlate significantly with CMJ scores, in such a way that in weeks with lower rates of perceived exertion, less km run and with higher training zone (i.e., more Zone 3 sessions) correspond with those weeks with higher CMJ performance. Similarly, our data shows that athletes with higher average season-long, session-RPE values significantly tend to be those who trained more km and had higher average season-long salivary cortisol concentrations. Some authors have proposed that elite athletes endurance training must consist of lower training volume to produce the desired

Table 3. Comparison of variables measured the week before the season best (SB) and season worst (SW) competition performances.

Variables	SAv	SB	SW	Hedge's g	95% CI	%
	Av ± SD	Av ± SD	Av ± SD			
CMJ (cm)	29.8±4.6 ^N	32.5±4.5 ^N	29.7±4.0 ^N	0.65	[1.9, 3.6]	+8.5**
Session-RPE (0–10)	5.8±4.5 ^N	5.6±1.3 ^N	6.6±0.8 ^N	0.94	[-1.9, -0.2]	-17.6*
Salivary free cortisol (ng/mL)	12.0±2.2 ^N	15.7±7.3 ^N	12.1±6.7 ^N	0.52	[-1.2, 8.3]	+22.9
Km run	84.9±5.9 ^N	75.8±24.4 ^N	87.2±22.8 ^N	0.48	[-26.8, 4.2]	-15.0
Training zone	1.8±0.8 ^N	1.9±0.4 ^N	2.0±0.4 ^N	0.21	[-0.4, 0.2]	-5.2

^N = Normally distributed variable (Kolmogorov-Smirnov test, p>0.05);

*p<0.05;

**p<0.001.

Abbreviations: SAv = average value for the season; SB = value measured the week before the season best competition performance; SW = value measured the week before the season worst competition performance; Av = average value; SD = standard deviation; 95% CI = 95% confidence interval of the differences between SB and SW values; % = percentage difference between SB and SW; CMJ = countermovement jump score; Session-RPE = rate of perceived exertion of the training session; km run = total weekly km run.

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adaptations [1,29]. For example, it has been proven in elite kayakers that a 1-year traditional endurance training programme produces lower increases in physical fitness than a 1-year block-periodisation endurance training programme with 50% less volume [1]. Similarly, it has been shown that resistance training performed until failure produces higher fatigue accumulation and lower increases in performance than an identical training regime in which half of the possible repetitions per set were executed [29]. Therefore, results in our study show that training with a higher volume and greater session-RPE correlate significantly with higher salivary cortisol concentrations and a lower performance in the CMJ.

Moreover, when analyzing the difference between the training load, salivary free cortisol and CMJ values measured the week before the season best and season worst competition performances, it is observed that, before the SB, athletes achieved higher CMJ scores than before the SW. Also, the CMJ before the SB was significantly higher than the season average, while the CMJ measured before the SW did not vary from the season average. Meanwhile, session-RPE measured before the SB was significantly lower than that measured before the SW. Furthermore, session-RPE before the SB was lower (although not significantly) than the season average, while the session-RPE before the SW was significantly higher than the season average. There were no significant differences in the other variables, although athletes trained 11.4 km less the week before the SB than before the SW performances. That is to say, the week before the best competition performance of the season, athletes trained with significantly lower session-RPE, achieved higher CMJ scores and ran more than 11 km less in comparison with the SW performance. In this sense, it was previously demonstrated that the reduction of training volume near to an important competition could improve physical performance of highly-trained athletes [30,31].

In summary, the weekly assessment of training load (using daily session-RPE, km run and training zone), salivary free cortisol and CMJ scores may help to control the training process of elite middle and long-distance runners using simple, non-invasive, systematic, field-based methods throughout a whole season. For the very first time, this study analyzes the relationships between training load,

salivary free cortisol concentrations and CMJ scores measured throughout 39 weeks of training by such athletes.

Practical Applications and Conclusions

This study reveals the significant relationships between average season values for CMJ scores, salivary free cortisol levels and session-RPE-athletes with higher salivary cortisol concentrations demonstrated a significant correlation with a tendency for lower CMJ scores and higher session-RPE values-. When observing the weekly average of the group, it was observed that the weeks in which higher CMJ scores were achieved significantly correspond to those with lower volume (km), higher training zone and lower session-RPE values. Finally, it was proven that CMJ scores were significantly higher and session-RPE values were significantly lower the week before the season best competition performance in comparison with the week before the season worst competition performance. The results of our study agree with those in other investigations which propose that training with lower volumes and less fatigue-inducing sessions are more effective in terms of increasing performance. Monitoring training load through daily session-RPE and weekly CMJ measurements could help control the training process of elite middle and long-distance runners. Furthermore, such variables can be measured throughout a whole season without interfering with the athlete's training using simple, non-invasive, field-based methods.

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Author Contributions

Conceived and designed the experiments: CBF JDCV. Performed the experiments: CBF JDCV. Analyzed the data: CBF CMTG JDCV. Contributed reagents/materials/analysis tools: CBF CMTG. Contributed to the writing of the manuscript: CBF CMTG.

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Research article

Seasonal Strength Performance and Its Relationship with Training Load on Elite Runners

Carlos Balsalobre-Fernández , Carlos M. Tejero-González and Juan del Campo-Vecino

Autonomous University of Madrid, Department of Physical Education, Sport and Human Movement, Madrid, Spain

Abstract

The aim of this study was to analyze the time-course of force production of elite middle and long-distance runners throughout an entire season and at the end of the off-season, as well as its relationships with training load and hormonal responses. Training load was recorded daily throughout an entire season by measuring and evaluating the session distance (km), training zone and session-RPE in a group of 15 elite middle and long-distance runners (12 men, 3 women; age = 26.3 ± 5.1 yrs, BMI = 19.7 ± 1.1). Also, basal salivary-free cortisol levels were measured weekly, and 50-metre sprints, mean propulsive velocity (MPV), mean propulsive power (MPP), repetition maximum (RM) and peak rate of force development (RFD) of half-squats were measured 4 times during the season, and once more after the off-season break. There were no significant variations in force production during the season or after the off-season break, except for the RFD (-30.2%, $p = 0.005$) values, which changed significantly from the beginning to the end of the season. Significant correlations were found between session-RPE and MPV ($r = -0.650$, $p = 0.004$), MPP ($r = -0.602$, $p = 0.009$), RM ($r = -0.650$, $p = 0.004$), and the 50-metre sprint ($r = 0.560$, $p = 0.015$). Meanwhile, salivary-free cortisol correlated significantly with the 50-metre sprint ($r = 0.737$, $p < 0.001$) and the RM ($r = -0.514$, $p = 0.025$). Finally, the training zone correlated with the 50-metre sprint ($r = -0.463$, $p = 0.041$). Session-RPE, training zone and salivary-free cortisol levels are related to force production in elite middle and long-distance runners. Monitoring these variables could be a useful tool in controlling the training programs of elite athletes.

Key words: Endurance, exercise, testing, physiology.

Introduction

Currently there is great interest in assessing the force production of middle and long-distance runners, because the benefits of resistance training for such athletes have been demonstrated (Aagaard and Andersen, 2010; Beattie et al., 2014; Ronnestad and Mujika, 2013; Saunders et al., 2004; Taipale et al., 2013). For example, it has been demonstrated that well-trained long-distance runners increased their running economy, as well as the time until exhaustion at the maximal aerobic velocity, after 8 weeks of a maximal strength training program using 4 sets of 4 RM conducted three times a week (Støren et al., 2008). Also, concurrent endurance and strength-endurance training (i.e., exercises with 3 sets of 20 repetitions at 40%RM) has shown to increase running economy on well-trained runners, although to a lesser extent than maximal or explosive strength (Sedano et al., 2013). Thus, given that elite athletes probably cannot affect much of an

improvement to their maximal oxygen consumption (Losnegard et al., 2013; Legaz-Arrese et al., 2005), strength training has been proposed as a necessary complement to increase performance in endurance events by improving other factors, such as running economy (Jung, 2003; Legaz-Arrese et al., 2005). Moreover, it has been demonstrated that strength and muscular power are related to running performance (Dumke et al., 2010; (Nummela et al., 2006). For example, the 50m sprint test has shown significant correlations with the 10-km performance on trained distance runners (Sinnett et al., 2001).

Monitoring the training process of distance runners is essential in order to observe their adaptations to training load and to avoid overtraining syndrome (Borresen and Lambert, 2009; Halson, 2014). Specifically, session-RPE and salivary-free cortisol have been proposed as time-efficient, non invasive methods to monitor training load because of its relationships with fatigue or stress (Crewther et al., 2009; Esteve-Lanao et al., 2005; Garcin et al., 2002; Papacosta and Nassis, 2011). Meanwhile, studying the evolution of force production throughout a whole season provides information about the effects of different training periods on athletic performance, which could prove very useful when programming training loads (Gorostiaga et al., 2006; Rousanoglou et al., 2013). Therefore, many studies have analyzed the evolution of force production throughout one or more seasons, especially in athletes whose sports demand high levels of strength, such as rugby, wrestling or football (Argus et al., 2009; Ratamess et al., 2013). However, to the best of our knowledge, there are no studies that analyze force production and its relationship with the training load of elite middle and long-distance runners during a whole season of concurrent endurance and strength training.

It is also of interest to study how the off-season break affects such athletes. For example, the off-season break has been observed to produce significant decreases in the vertical jump or short-sprint performance of well-trained athletes (Caldwell and Peters, 2009). In this regard, information about the changes in force production after the off-season break may help to design strategies to minimize the decrease in these performance indicators so athletes could start the season in optimum physical condition (McMaster et al., 2013; Smart and Gill, 2013). To this end, the assessment of force production on elite middle and long-distance runners throughout a whole season and at the end of the off-season break is of great importance for programming their training loads. Therefore, the purpose of this investigation was to analyze force

production and its relationship with the training load of such athletes during a whole season of concurrent endurance and strength training

Methods

Subjects

Fifteen elite middle and long-distance runners were assessed for 50-metre sprint and force production of half-squats 4 times during a competitive season (October - July). Each measurement was taken at the end of each training period. These variables were also measured once more at the end of the off-season (September). Training load (assessed daily, using distance run, training zones and session-rate of perceived effort, RPE) and basal salivary free cortisol levels (once a week) were measured throughout the whole season. Average values for both training load and basal salivary free cortisol levels were calculated for each training period. Differences between periods with respect to 50-metre sprint, half-squat, training load and basal salivary free cortisol levels, as well as the correlations between these variables, were analyzed. The study protocol complied with the Declaration of Helsinki for Human Experimentation, and the Ethics Committee of the first author's University approved all procedures.

Participants

The study participants were 15 elite middle and long-distance runners from the High Performance Sports Center Madrid (12 men, age = 25.6 ± 5.4 yrs., body mass index [BMI] = $20.0 \pm 1.0 \text{ kg}\cdot\text{m}^{-2}$; 3 women; age = 29 ± 2.0 yrs, BMI = $18.6 \pm 0.2 \text{ kg}\cdot\text{m}^{-2}$), with personal bests in outdoor 1500-metres between 3:38 - 3:58 min (men, i.e., 84-94% of the world record) and 4:12 - 4:18 min (wom-

en, i.e., 87-90% of the world record). Participation of the athletes was voluntary and anonymous. All participants signed an informed consent form prior to participation in the study.

Instrumentation

A pair of Racetime 2 Light photocells (Microgate Srl, Italy) were used to measure the 50-metre sprint and the half-squat force production was measured with a T-Force linear velocity transducer (Ergotech, Spain). Saliva samples were collected using Salivette® tubes (Sarstedt, Germany). Salivary free cortisol values were obtained using Free Cortisol in Saliva ELISA Assay kits (Demeditec Diagnostics, Germany).

Procedures

Training periods

The season was divided into 4 training periods, each approx. 2 - 3 months long. The season was periodised so that Periods 1 (P1) and 2 (P2) focused on long-distance runs while Periods 3 (P3) and 4 (P4) had more interval training sessions with short-distance runs (i.e., sets of 200 - 300 metres). Athletes completed 7 - 10 endurance training sessions per week. See Figure 1 for more details. Also, athletes completed two 90min. resistance training sessions per week consisting of 9 upper and lower body exercises with 3 sets of 15 - 20 RM, with rest between sets of 90s. Training exercises used were: half-squats, jump squats, leg extension, leg curl, calf raises, bench press, lat-pull down, biceps curl and push press. The exact resistance training program was used in every training period with no tapering phases. Resistance training intensity (i.e., 15 - 20 RM) was chosen to work strength-endurance capacities (Sedano et al., 2013).

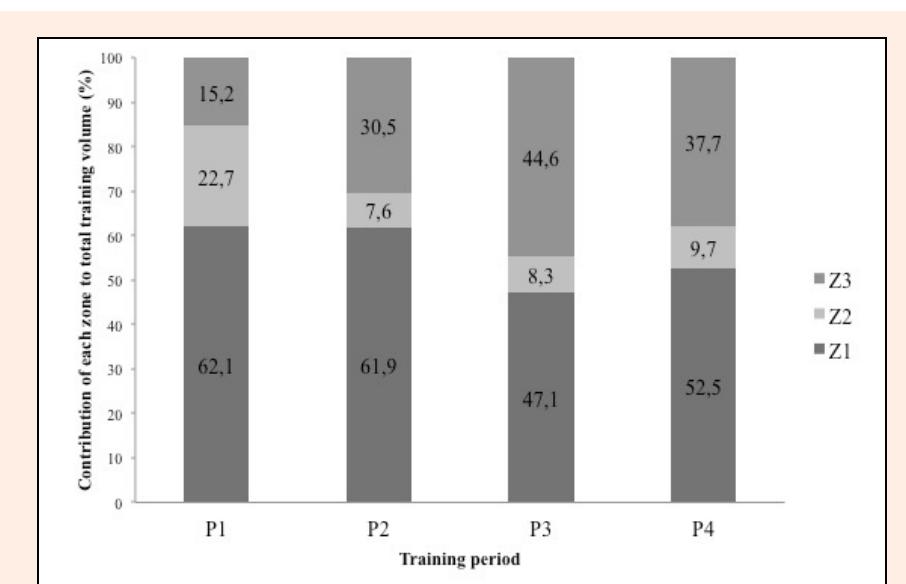


Figure 1. Distribution of endurance training zones throughout the season (% of total training distance, in km). Z1: training zone 1 (long-distance continuous training or interval training [sets with 4 - 6 km], running paces between 3:45 - 3:10 min/km); Z2: training zone 2 (middle-distance interval training [sets with 1 - 3 km], running paces between 3:10 - 2:50 min/km); Z3: training zone 3 (short distance and sprint interval training [sets with 200 - 600 m], with running paces of sub 2:50 min/km up to maximum sprint).

Testing

The 50-metre sprint and half-squat force production were measured, in that order, at the end of each training period and at the end of the off-season break (OS) (i.e., five assessment points during the study). All measurements were performed at the same time of the day, on the same day of the week and in the same facilities of the High Performance Sports Center Madrid.

50-metre sprint measurement: After a standard 20-minute warm-up, consisting in 10 minutes of continuous running, plus dynamic stretches and preparatory vertical jumps, athletes completed 2 progressive 50-metre sprints, firstly at moderate, then at high speed as a warm-up exercise. They then completed two maximal speed 50-metre sprints from a standing start, located 1 metre before the starting photocell. Timing gates were placed at 0m and 50m. Athletes were instructed to run as fast as possible without stopping until they passed the finish photocell. Attempts were separated by two minutes of passive rest. The faster of the two attempts was recorded in seconds. The coefficient of variation (CV) of the two attempts was 0.33 - 1.2%.

Half-squat force production: A progressive test from 50 to 100 kg was employed to measure half-squat force production, increasing the load by 10 kg for each new attempt, giving a total of 6 different loads (50, 60, 70, 80, 90 and 100 kg loads). Half-squats were performed on a Smith machine, with the linear position and velocity transducer attached to the barbell and the cable perpendicular to the floor. Athletes performed two repetitions of each load (CV = 5.4 - 6.7%) with the barbell on their upper-back, with feet hip-width apart, flexing the knees at 90° for the eccentric phase and executing the concentric phase as quickly as possible. Two minutes of passive rest separated each attempt. Total mean propulsive velocity (MPV), mean propulsive power (MPP), and peak rate of force development (RFD) were recorded. Also, the repetition maximum (RM) was estimated by the linear transducer software, which uses the relationship between barbell MPV and relative intensity (i.e., percent of RM) to calculate the values (Sanchez-Medina and González-Badillo, 2011). Using the MPV has been observed to be the most accurate method for estimating the RM with submaximal loads (González-Badillo and Sánchez-Medina, 2010).

Salivary free cortisol

To establish the basal cortisol concentration (in ng·mL⁻¹), athletes collected a saliva sample when they awoke, with an empty stomach, once a week throughout the whole of the competitive season corresponding to the study. Athletes chewed the cotton inside the Salivette® tube for 60 seconds, and then they stored the sample at -20 °C (according to manufacturer's instructions) until they brought it to the High Performance Sports Center. All measurements were taken on the same day of the week, at the same time and under the same environmental conditions (i.e., athletes homes). Average values for each training period of the study, as well as for the whole season were calculated. All samples were stored at -20 °C and analyzed at the Biochemical Laboratory of the Polytechnic

University of Madrid (Official Lab. Number 242 in the Region of Madrid).

Training load

Distance run (in km) training zones (according to session mean running speed) and session-RPE (Foster, 1998) (0-10) were used to measure the daily training load. Daily distance run was registered using each athlete's training program. If an athlete didn't meet the training program, the daily distance run was modified according to what the athlete did actually complete. Daily training zone was registered according to session running paces: training zone 1 (running paces between 3:45 - 3:10 min/km); training zone 2 (running paces between 3:10 - 2:50 min/km); training zone 3 (running paces of sub 2:50 min/km up to maximum sprint). Session-RPE was assessed 10 minutes after the training session by asking: "How hard was the training session today, with 0 being very, very light and 10 being very, very hard?" Average values were calculated for each training period in the study, as well as for the whole season.

Statistical analyses

The normality of the variables was tested using the Kolmogorov-Smirnov (K-S) test. One-way repeated measures analysis of variance (ANOVA) was used in order to analyze possible differences between the average values of the variables for each training period. The main effects were compared using the post-hoc Bonferroni method, estimating the percentage of change (%) between P1-P2, P2-P3, P3-P4, P1-P4 and P4-OS. The Pearson correlation coefficient, unilateral contrast, was used to analyze the relationship between the variables. The level of significance was set at $p \leq 0.05$. All calculations were performed using IBM® SPSS® Statistics 22 software (IBM Co., USA).

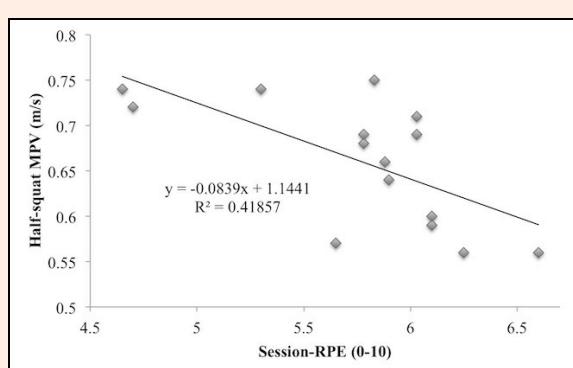


Figure 2. Correlation between session-RPE and half-squat mean propulsive velocity (MPV).

Results

Descriptive data is presented for each training period on Table 1. With respect to strength-related variables, the repeated measures ANOVA reported that, throughout the course of the season, there were no significant differences in the following variables: time in the 50-metre sprint,

Table 1. Periods and season average values for each variable. Data are means (\pm SD).

Variables		P1	P2	P3	P4	Off-season	Season average
Strength-related variables	Sprint (s) ^N	Men Women Total	6.56 (.28) 7.21 (.41) 6.69 (.40)	6.55 (.30) 7.07 (.50) 6.65 (.40)	6.63 (.30) 7.18 (.56) 6.75 (.44)	6.55 (.20) 7.35 (.56) 6.72 (.49)	6.58 (.40) 7.40 (.36) 6.69 (.41)
	MPV (m·s ⁻¹) ^N	Men Women Total	.66 (.60) .58 (.03) .64 (.06)	.68 (.70) .59 (.04) .66 (.06)	.69 (.80) .62 (.06) .67 (.09)	.65 (.60) .60 (.07) .66 (.08)	.65 (.80) .57 (.01) .64 (.08)
	MPP (W) ^N	Men Women Total	602 (73) 498 (29) 586 (86)	588 (92) 512 (66) 573 (109)	606 (101) 523 (66) 584 (110)	568 (84) 494 (69) 571 (78)	568 (100) 439 (13) 543 (116)
	RM (kg) ^N	Men Women Total	115 (6) 104 (7) 112 (8)	112 (5) 105 (7) 111 (9)	112 (6) 106 (6) 109 (8)	111 (6) 104 (8) 110 (7)	109 (5) 100 (4) 107 (7)
	RFD (N·s ⁻¹) ^N	Men Women Total	1704 (601) 1296 (331) 1378 (251)	1564 (622) 1043 (118) 1164 (87)	1359 (501) 1137 (378) 1188 (308)	833 (166) 1193 (144) 962 (212)	1080 (452) 834 (121) 842 (192)
	KM (week) ^N	Total	95.2 (.9)	89.6 (8.7)	85.6 (8.1)	66.6 (12.5)	---
	Zone (week) ^N	Total	1.50 (.03)	1.70 (.08)	2.00 (.14)	1.80 (.11)	---
	Session-RPE (week) ^N	Men Women Total	5.9 (.7) 6.0 (.7) 6.0 (.7)	5.9 (.3) 6.2 (.5) 6.0 (.4)	5.4 (1.0) 6.3 (.5) 5.6 (.6)	5.3 (1.1) 6.3 (.3) 5.5 (1.1)	5.6 (.5) 6.2 (.3) 5.9 (.4)
Salivary-free cortisol	CORT ^N (ng·ml ⁻¹)	Men Women Total	11.1 (2.2) 12.1 (1.7) 11.3 (2.2)	8.9 (2.4) 10.9 (2.3) 9.4 (2.4)	11.1 (2.6) 10.7 (3.7) 11.0 (2.8)	19.3 (3.6) 17.2 (.7) 18.9 (3.4)	12.0 (1.8) 3.6 (4.3) 12.1 (2.3)

N = Normally distributed variable (Kolmogorov-Smirnov test, $p > 0.05$). Abbreviations: Sprint = 50-metre sprints; MPV = mean propulsive velocity of half-squats; MPP = mean propulsive power of half-squats; RM = Repetition Maximum of half-squats; RFD = peak rate of force development of half-squats; KM (week) = average training distance in km per week; Zone (week) = average training zone per week; Session-RPE (week) = average session-rate of perceived exertion per week; CORT = Average basal salivary free cortisol levels.

MPV, MPP or RM of half-squats (all > 0.05). In contrast, a 30.2% decrease in the RFD of half-squats ($p = 0.005$) was observed between the beginning (P1) and the end (P4) of the season (Table 2).

Based on the season-long average value of each variable, several correlations were apparent. RPE correlated significantly with MPV ($r = -0.650$, $p = 0.004$) (Figure 2), MPP ($r = -0.602$, $p = 0.009$) and RM ($r = -0.650$, $p = 0.004$) of half-squats, and also with the 50-metre sprint ($r = 0.560$, $p = 0.015$). Meanwhile, salivary free cortisol correlated significantly with the 50-metre sprint ($r = 0.737$, $p < 0.001$) and the half-squat RM ($r = -0.514$, $p = 0.025$). Finally, the average training zone correlated with the 50-metre sprint ($r = -0.463$, $p = 0.041$). See Table 3 for more details.

Discussion

The analysis of the correlations between variables indicated that training load and salivary free cortisol correlated significantly with force production throughout the season. In average terms, athletes with greater session-RPE values throughout the season had significantly lower levels of MPV, MPP and RM of half-squats, as well as slower times in the 50-metre sprint than those who declared lower session-RPE. In this sense, session-RPE was demonstrated as the training load parameter that correlates most significantly with force production in elite middle and long-distance runners. Using session-RPE to monitor training load has been used widely and in a variety of sports (Haddad et al., 2011; Milanez et al., 2011); however, to the best of our knowledge, this is the first study that analyses the relationship between session-RPE and force production of elite middle and long-distance runners throughout the course of an entire season.

Table 2. Percentage of change in the studied variables throughout the different training periods.

	P1-P2	P2-P3	P3-P4	P1-P4	After Off-Season
Sprint	-.5%	+1.5%	-.4%	-.4%	+.4%
MPV	+3.1%	+1.5%	-1.5%	+3.1%	-3.1%
MPP	-2.2%	+1.9%	-2.3%	-2.6%	-4.9%
RFD	-15.5%	+2.1%	-19.9%	-30.2%*	-12.9%
RM	-.9%	-1.1%	+.4%	-1.6%	-2.39%
CORT	-16.8%*	+17.0%	+71.8%*	+67.2%*	-----
Session-RPE (week)	+.0%	-6.7%	-1.8%	-.8.3%	-----
KM (week)	-5.8%	-4.4%	-22.2%**	-30.0%**	-----
Zone (week)	+13.3%**	+17.6%**	-8.5%**	+22.0%**	-----

Abbreviations: Sprint = 50-metre sprints; MPV = mean propulsive velocity of half-squats; MPP = mean propulsive power of half-squats; RM = Repetition Maximum of half-squats; RFD = peak rate of force development of half-squats; KM (week) = average training distance in km per week; Zone (week) = average training zone per week; Session-RPE (week) = average session-rate of perceived exertion per week; CORT = Average basal salivary free cortisol levels. * $p < 0.05$; ** $p < 0.001$

Table 3. Pearson correlation coefficient (*r*) between the average values of the studied variables.

	SPRINT	MPV	MPP	RFD	RM	CORT	RPE	KM	ZONE
SPRINT	---	-0.769**	-0.795**	-0.247	-0.823**	0.737**	0.560*	0.072	-0.463*
MPV		---	0.910**	0.462*	0.918**	-0.335	-0.650**	-0.142	0.288
MPP			---	0.478*	0.960**	-0.430	-0.602**	0.013	0.269
RFD				---	0.414	-0.033	-0.415	-0.117	-0.192
RM					---	-0.514*	-0.650**	-0.134	0.408
CORT						---	0.318	0.053	-0.528*
RPE							---	-0.034	-0.082
KM								---	-0.597**

Abbreviations: Sprint = 50-metre sprints; MPV = mean propulsive velocity of half-squats; MPP = mean propulsive power of half-squats; RFD = peak rate of force development of half-squats; RM = Repetition Maximum of half-squats; CORT = basal salivary free cortisol levels; RPE = session-rate of perceived exertion per week; KM = training distance in km per week; ZONE = training zone per week.* p < 0.05; ** p < 0.001

With respect to the other variables used to monitor training load (i.e., average weekly distance, in km, and training zone), our study has uncovered a significant correlation between average training zone and the 50-metre sprint; where athletes who trained in higher training zones had significantly faster times in the 50-metre sprint. This agrees with other studies which have proposed that higher training intensities with lower volumes may be more effective in increasing force production in high-level endurance athletes (García-Pallarés et al., 2010). With respect to basal salivary free cortisol levels, our study demonstrates that athletes with significantly lower levels had significantly higher values for half-squat RM and faster times in the 50-metre sprint. Analysis of salivary free cortisol levels has been used widely in the literature because of its capacity to monitor fatigue states and stress levels, coupled with the fact that it is a non-invasive measurement (Gomes et al., 2013). Moreover, it has been demonstrated that salivary free cortisol levels in wrestlers correlate with power production in the power-clean (Passelergue and Lac, 2012). Our results further the knowledge in this respect, showing for the first time that salivary free cortisol correlates significantly with maximum strength and 50-metre sprint performance in elite middle and long-distance runners.

The MPV, MPP and RM of half-squats remained unchanged across the four training periods. Nevertheless, some studies have demonstrated that concurrent strength and endurance training can produce increases in strength whilst avoiding the effects of interference between the different training regimes (García-Pallarés and Izquierdo, 2011; Taipale et al., 2013). For example, it has been shown that concurrent training increases leg-press RM and the running economy of well-trained elite runners (Francesca Piacentini et al., 2013). However, that study used 2 resistance-training sessions plus 4 or 5 endurance sessions per week, whereas the athletes in our study performed 2 resistance-training sessions plus 7 - 10 endurance-training sessions per week. Therefore, in our study the resistance-training was 20-28% of all training sessions (endurance and strength) per week. Some authors have proposed that concurrent training should be composed of a block periodization with about 50% of total training focused on strength in order to increase both strength and endurance capacities (García-Pallarés and Izquierdo, 2011), because high-volume endurance training may have a major influence on strength gains (Rønnestad et al., 2012). The commonest type of concurrent training used in the literature employs heavy-load and low repetitions (i.e.,

4 - 5 RM) to develop the neural factors of strength (Aagaard and Andersen, 2010; Francesca Piacentini et al., 2013). This type of strength training appears to avoid the interferences between strength and endurance capacities better than others, and it attenuates the transition to type I fibres produced by endurance training (García-Pallarés and Izquierdo, 2011). However, middle and long-distance runners in our study performed a strength-endurance based resistance-training programme, with multiple exercises and high repetitions per set (up to 20 RM), which seems to be unsuitable for enhancing strength and power of these population because of its low intensity (Hartmann et al., 2009).

Furthermore, although strength variables in half-squats didn't change, the RFD decreased significantly from the beginning to the end of the season. As demonstrated, the RFD represents the ability of athletes to produce force in a unit time, which is commonly called explosive strength (Holtermann et al., 2007; Taipale et al., 2013). On one hand, it is known that the RFD is positively associated with the quantity of type II muscle fibres (Korhonen et al., 2006) and, on the other hand, endurance training has shown to produce transition to type I fibres (Gehlert et al., 2012; Thayer et al., 2000). In this sense, non-significant changes in force production in the athletes in our study may be the result of the high-volume endurance training, common for elite long-distance runners, and the strength-endurance based resistance-training programmes they conducted throughout the season. However, given the lack of research in this matter, more studies are required to establish optimum, season-long, resistance-training programmes for elite middle and long-distance runners.

At the end of the off-season break, all strength-related variables remained significantly unchanged with respect to the end of the season. During a one-month off-season break, athletes in our study participated in active, unstructured rest in which they conducted non-specific physical activities of their choice, such as cycling, hiking or swimming, 3 times per week. Therefore, our data demonstrates that a month of active rest is not enough to cause a significant decrease in the force production of elite middle and long-distance runners. In this sense, given that resistance-training programmes during the off-season have been shown to be important in avoiding decreases in performance caused by detraining (Smart and Gill, 2013), it would be interesting to study if a resistance-training programme during the off-season that could even increase the force production of such athletes.

However, there are a number of limitations within the study. Strength training has been probed to increase running economy (Beattie et al., 2014; Ronnestad and Mujika, 2013) and thus it would have been useful to measure running economy in order to analyze its relationship with force production throughout the whole season. Additionally, the sample size in our study is too small to allow relevant comparatives between different events (for example, 800m.vs 3000m. steeplechase vs. 10000m.) and genders. Thus, future studies should utilize larger sample sizes and more tests (such as running economy) to analyze the role of force production on the training process of elite middle and long-distance runners. To the best of our knowledge, this is the first study which analyzes the effects of an entire season plus the off-season break, on the force production of elite middle and long distance runners.

Conclusion

In conclusion, our data also demonstrates that session-RPE, training zone and salivary free cortisol levels correlate significantly with many of the strength-related variables studied. Monitoring training loads through session-RPE is a suitable and simple method for controlling the training process in high-level middle and long-distance runners. Also, it has been observed that a month of active rest during the off-season break is enough to prevent decreases in force production of such athletes. These findings further the knowledge about the training process of high-level middle and long-distance runners and its relationship with force production. This could prove very beneficial to both coaches and trainers.

Acknowledgments

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Key points

- Session-RPE, training zone and salivary free cortisol levels correlate significantly with strength-related variables in middle and long-distance elite runners.
- A month of active rest during the off-season break is enough to prevent decreases in force production of such athletes.
- Monitoring training loads through session-RPE is a suitable and simple method for controlling the training process in elite middle and long-distance runners.

AUTHORS BIOGRAPHY

	Carlos BALSALOBRE-FERNÁNDEZ Employment Autonomous University of Madrid, Department of Physical Education, Sport and Human Movement, Madrid, Spain Degree MSc Research interests Strength training and physical performance in elite athletes. E-mail: carlos.balsalobre@uam.es
	Carlos Mª TEJERO-GONZÁLEZ Employment Autonomous University of Madrid, Department of Physical Education, Sport and Human Movement, Madrid, Spain Degree PhD Research interests Statistics applied to Sports Sciences. E-mail: carlos.tejero@uam.es
	Juan del CAMPO-VECINO Employment Autonomous University of Madrid, Department of Physical Education, Sport and Human Movement, Madrid, Spain Degree PhD Research interests Performance analysis of elite track&field athletes. E-mail: juan.delcampo@uam.es

✉ Carlos Balsalobre-Fernández

Autonomous University of Madrid, Department of Physical Education, Sport and Human Movement, Madrid, Spain

Hormonal and Neuromuscular Responses to High-Level Middle- and Long-Distance Competition

Carlos Balsalobre-Fernández, Carlos Mª Tejero-González, and Juan del Campo-Vecino

Purpose: The purpose of this study was to analyze the effects of high-level competition on salivary free cortisol, countermovement jump (CMJ), and rating of perceived exertion (RPE) and the relationships between these fatigue indicators in a group of elite middle- and long-distance runners. **Method:** The salivary free cortisol levels and CMJ height of 10 high-level middle- and long-distance runners (7 men, 3 women; age 27.6 ± 5.1 y) competing in 800-m, 1500-m, 3000-m, or 5000-m events in the 2013 Spanish National Championships were measured throughout a 4-wk baseline period, then again before and after their respective races on the day of the competition. Athletes' RPE was also measured after their races. **Results:** Cortisol increased significantly after the race compared with the value measured 90 min before the race ($+98.3\%$, $g = 0.82$, $P < .05$), while CMJ height decreased significantly after the race (-3.9% , $g = 0.34$, $P < .05$). The decrease in CMJ height after the race correlates significantly with the postcompetition cortisol increase ($r = .782$, $P < .05$) and the RPE assessment ($r = .762$, $P < .01$). **Conclusions:** Observed differences in CMJ height correlate significantly with salivary free cortisol levels and RPE of middle- and long-distance runners. These results show the suitability of the CMJ for monitoring multifactorial competition responses in high-level middle- and long-distance runners.

Keywords: athletic training, physical performance, endurance training, exercise physiology, muscle function, sport

Acute fatigue is defined as a multifactorial exercise-induced impairment of performance.¹ Monitoring the level of acute fatigue is vitally important to sport performance. First, it helps when designing training programs that reduce its appearance and, second, in the development of recovery strategies that will allow the athlete to keep training and competing at the highest level.¹ In this regard, the literature describes a variety of methods to evaluate several factors of acute fatigue in middle- and long-distance runners, such as measuring blood lactate concentration,² rating of perceived exertion (RPE),¹ cortisol levels,³ or countermovement-jump (CMJ) height.⁴ Although measurement of blood lactate concentration is probably the most typical method of assessing exercise intensity,⁵ its invasive nature is a major drawback when assessing athletes' degree of fatigue in full competition situations. Therefore, it would be beneficial if other, simpler, and more user-friendly methods were available for evaluating the degree of effort produced by middle- and long-distance runners in competition.

In this respect, the RPE is probably the easiest and quickest way to monitor the degree of effort in running exercises, and thus its use is very common in the scientific literature.⁵ For example, Stellingwerff⁶ used, among other variables, RPE to assess the training intensity of elite marathon runners during a training cycle. Other authors have found that RPE complements blood lactate measurements, so that it is possible to detect states of overreaching in young middle-distance runners.⁷ Analysis of salivary free cortisol is useful due to its ease of measurement and its ability to assess physical and mental stress that may lead fatigue.⁸ Hence, many authors have assessed cortisol levels by taking saliva samples after various types of training and competition situations.^{9–11} For example, it has been

proven that marathon runners produce lower levels of cortisol than middle-distance runners after 40 minutes running at 80% of their maximal oxygen uptake, which demonstrates the greater adaptation and the lower degree of stress that long-distance runners experience in a continuous workout.³ Finally, assessing CMJ as an indicator of neuromuscular fatigue is being increasingly used in a variety of sports.^{12–14} For example, it has been shown that running a marathon causes a 16% decrease of CMJ in amateur runners¹⁵ compared with ~13% in elite competitors.⁴ A significant relationship between the decline in sprint speed of elite sprinters across a set of intermittent short sprints and a decrease in CMJ height has also been demonstrated.¹³ However, there is a lack of studies in the literature that analyze the degree of different factors of fatigue of middle- and long-distance runners during high-level competition. Moreover, considering that competition situations produce significantly higher stress levels than training,^{16,17} the degree of different factors of acute fatigue during high-level competition must be analyzed to further scientific understanding in this area.

Therefore, the purpose of this research was to analyze how RPE, salivary free cortisol levels, and CMJ height respond to the most important competition of the season in a group of high-level middle- and long-distance runners. Our hypotheses were that CMJ height and cortisol levels would be significantly higher on the day of the competition than during a baseline control period of 4 weeks, CMJ height would be lower and the salivary free cortisol levels higher after the competition, and there would be a significant correlation between those variables.

Methods

Subjects

The sample consisted of 10 middle- and long-distance runners (N = 10, 7 men, 3 women, age 27.6 ± 5.1 y) who participated in the

The authors are with the Department of Physical Education, Sport and Human Movement, Autonomous University of Madrid, Madrid, Spain. Address author correspondence to Carlos Balsalobre-Fernández at carlos.balsalobre@uam.es.

2013 Spanish National Athletics Championship. All of them had competed in international events and had personal bests in the 1500-m between 3:38 and 3:47 minutes for men and 4:12 and 4:23 minutes for women. The study protocol complied with the Declaration of Helsinki for Human Experimentation and was approved by the ethics committee at the Autonomous University of Madrid. Written informed consent was obtained from each subject before participation.

Design

This study used paired-samples comparisons of means with a baseline period of 4 weeks. Free cortisol in saliva measured on awakening (basal cortisol) and before and after the competition, CMJ height before and after the competition, and RPE after the competition were all measured and recorded. Data for the baseline period were collated by measuring the basal cortisol and CMJ height once a week for 4 weeks before the competition, so that the mean values could be compared with the values measured on the day of the competition. See more details in Table 1.

Measures

Salivary Free Cortisol. To establish the basal cortisol (in $\mu\text{g}/\text{mL}$), athletes collected a saliva sample when they awoke (about 9 AM), with an empty stomach, once a week during the 4 weeks before the competition and on the competition day using Salivette tubes (Sarstedt, Germany). Athletes chewed the cotton inside the Salivette tube for 60 seconds and then stored the sample at -20°C for 1 hour before subsequently bringing it to the laboratory for analysis. All measurements were performed on the same day of the week, at the same time and under the same environmental conditions. In addition, saliva samples were collected when athletes awoke (about 9 AM) and 90 minutes before and 10 minutes after the race (which started at 7 PM) on the competition day. The samples were then stored at -20°C according to the manufacturer's instructions. All samples were analyzed at the biochemical laboratory of the Polytechnic University of Madrid (official laboratory number 242 in the Region of Madrid).

Countermovement Jump. During the 4 weeks before the competition, we measured the height reached (in cm) in the CMJ immediately before training sessions, on the same day that saliva samples were collected. The CMJ was performed with hands on

hips, knees straight in the flight phase, while trying to jump as high as possible. All measurements were taken on the same day of the week, at the same time and under the same environmental conditions. On the day of the competition, CMJ height was measured 90 minutes before and 10 minutes after the race, that is, immediately after collecting the saliva sample of each athlete. Although CMJ was measured at different hour on baseline than on the competition day, it seems that time of day has no effects on vertical-jump performance.¹⁸ The mean of 3 attempts was recorded. Reliability of the measurements was calculated using the intraclass correlation coefficient ($\text{ICC} = .979\text{--}.990$, $P < .001$).

Rating of Perceived Exertion. While saliva samples were being collected after the race, RPE was assessed using the Borg 0-to-10 scale by asking, "How hard was the race, with 0 being very, very light and 10 extremely heavy?"

Statistical Analysis

For the comparison of means, we used a paired-samples *t* test. For calculation of the effect size, we used the Hedge *g*.¹⁹ To analyze the relationship between the variables, we used the Pearson (*r*) correlation coefficient, unilateral contrast. The level of significance was set at .05. All calculations were performed using IBM SPSS Statistics 20 software (IBM Corp, USA).

Results

Basal Cortisol and CMJ Height at Baseline Versus Competition Day

The comparison of means showed that the value of basal cortisol was significantly higher on competition day than during the baseline period ($+117.5\%$, $g = 1.59$, $P < .001$), and the CMJ performed before the competition was significantly higher than that of the baseline CMJ ($+6.5\%$, $g = 0.47$, $P < .001$). See Figure 1.

Pre Versus Postcompetition Salivary Free Cortisol Levels and CMJ Height

CMJ height decreased significantly after the race (-3.9% , $g = 0.34$, $P = .025$), whereas cortisol levels were significantly higher after the race than 90 minutes before the race ($+98.3\%$, $g = 0.82$, $P = .027$). See Figure 2.

Table 1 Countermovement-Jump Height, Levels of Salivary Free Cortisol, and Distribution of Training Load During the Baseline Weeks

	Wk 1	Wk 2	Wk 3	Wk 4
Countermovement-jump height (cm)	31.2 ± 5.5	31.4 ± 4.7	30.4 ± 4.3	31.8 ± 5.2
Salivary free cortisol ($\mu\text{g}/\text{mL}$)	12.4 ± 6.7	11.8 ± 6.9	13.1 ± 5.6	17.4 ± 10.4
Distance per week (km)	56.4 ± 15.2	88.8 ± 17.9	72.6 ± 6.3	58.0 ± 19.3
Zone 1 ^a (% of km/wk)	67.6	50.0	50.0	45.4
Zone 2 ^b (% of km/wk)	0.0	11.5	25.0	12.0
Zone 3 ^c (% of km/wk)	32.4	38.5	25.0	42.6

^a Long-distance continuous training or interval training (sets with 4–6 km), running paces 3:45–3:10 min/km. ^b Middle-distance interval training (sets with 1–3 km), running paces 3:10–2:50 min/km. ^c Short-distance and sprint interval training (sets with 200–600 m), with running paces under 2:50 min/km to maximal sprint.

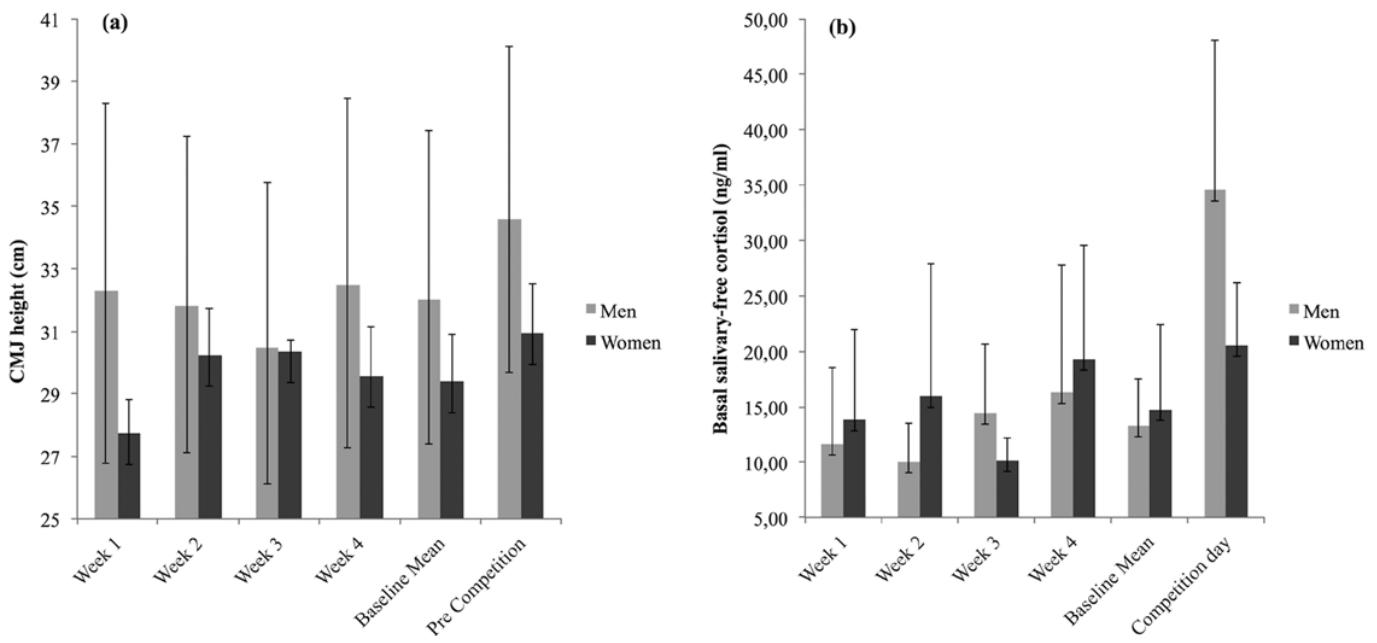


Figure 1 — (a) Countermovement-jump (CMJ) height and (b) basal cortisol levels during the baseline period and on competition day, mean \pm SD.

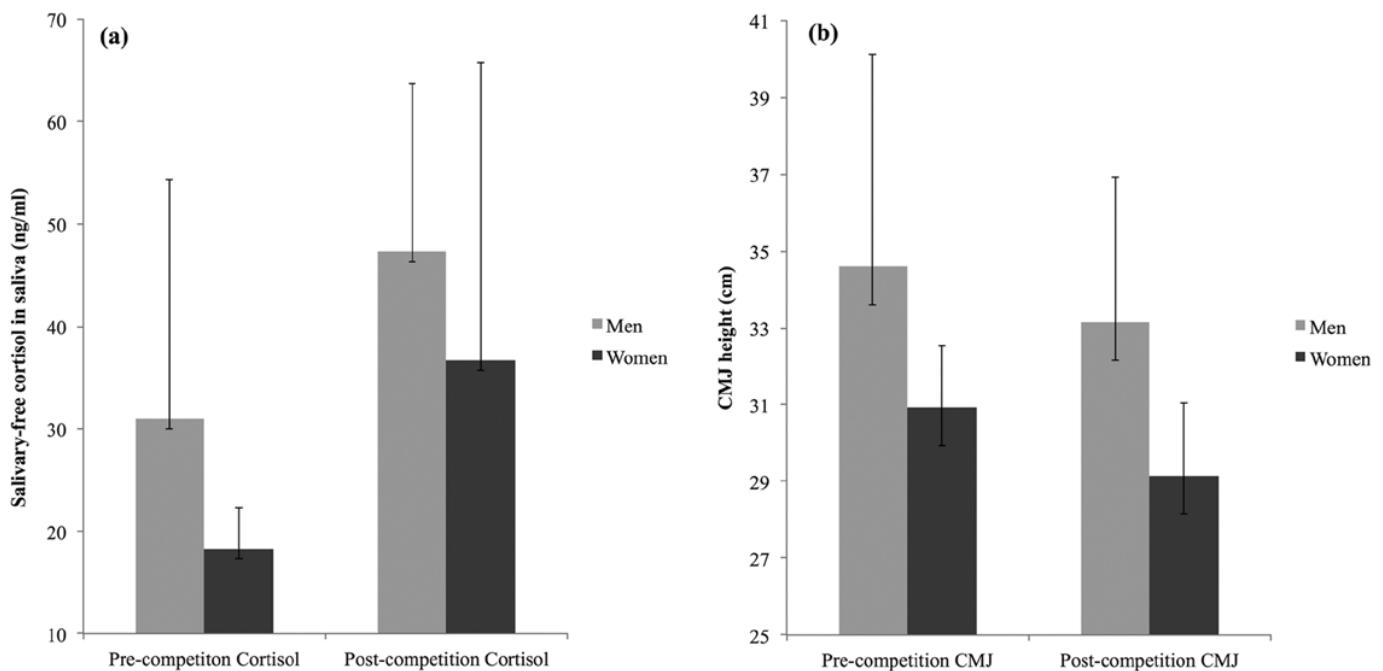


Figure 2 — (a) Levels of salivary free cortisol and (b) countermovement-jump (CMJ) height before and after the competition, mean \pm SD.

Relationships Between RPE, CMJ, and Salivary Free Cortisol

A significant and positive correlation was observed between (1) the increase in basal cortisol (from the baseline to the competition day) and the increase in CMJ height ($r = .688, P = .010$), (2) the decrease

in postcompetition CMJ height compared with those measured precompetition (CMJ decrease) and the postcompetition increase in salivary free cortisol levels ($r = .782, P = .011$), (3) the CMJ decrease and RPE ($r = .762, P = .002$), and (4) the postcompetition increase in salivary free cortisol levels and the competition distance ($r = .67, P = .034$). See Figure 3.

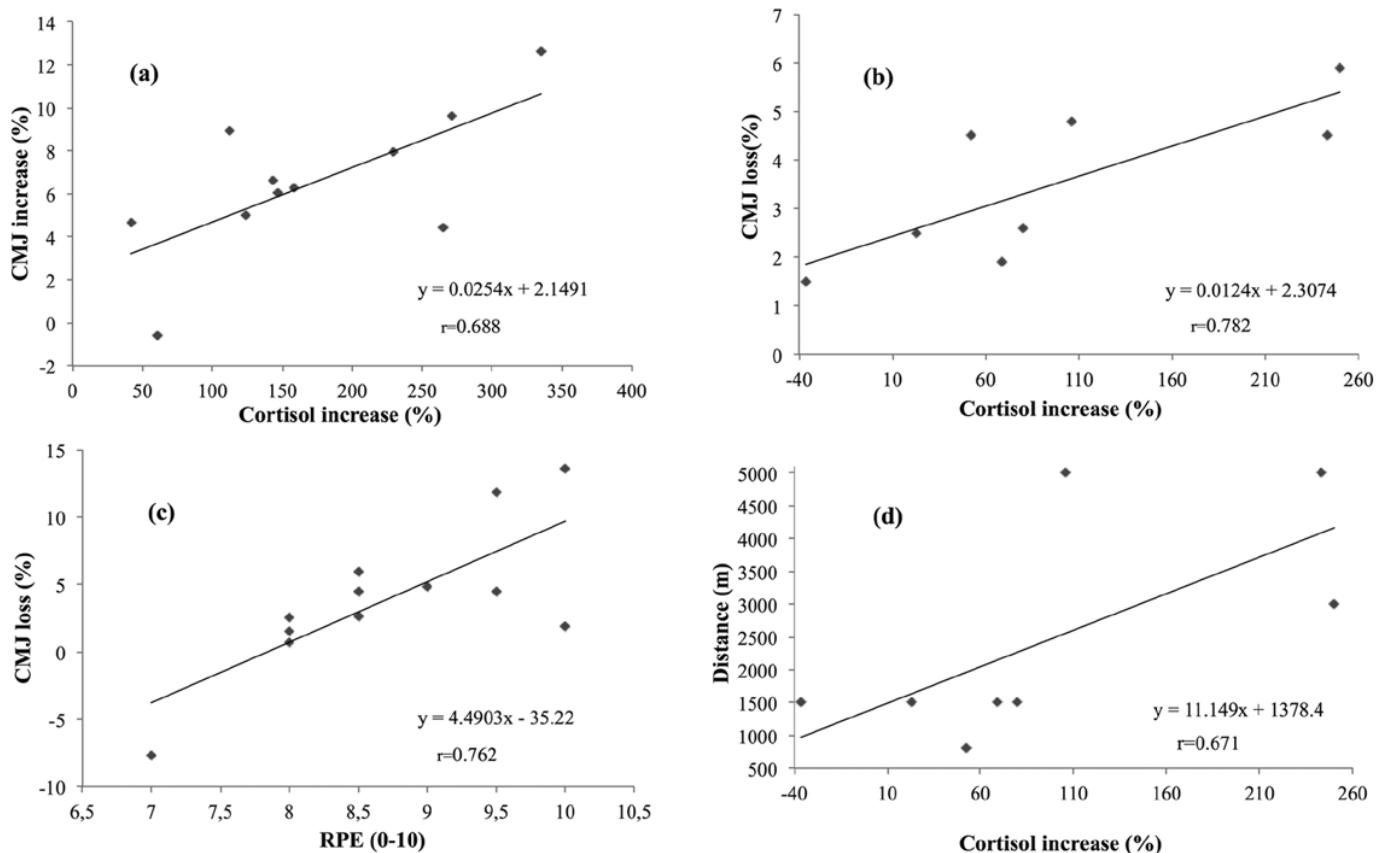


Figure 3 — Correlations of (a) the increase in countermovement-jump (CMJ) height and cortisol levels between the baseline period and day of competition, (b) postcompetition CMJ decrease and cortisol increase, (c) postcompetition CMJ decrease and rating of perceived exertion (RPE), and (d) the postcompetition cortisol increase and competition distances.

Discussion

The results of our study show that athletes had significantly higher cortisol levels and lower CMJ height after the competition than equivalent measurements taken 90 minutes before the race. Similar cortisol responses during competitive situations have been observed on numerous occasions across various types of sport.^{20,21} In addition, although running exercises may produce some type of postactivation potentiation effects,¹² a decrease on CMJ immediately after competition is common in distance runners.⁴ However, this study provides new data that, to our knowledge, have never been studied in high-level middle- and long-distance runners. The difference between precompetition and postcompetition CMJ height (CMJ decrease) shows significant and positive correlation with the difference between precompetition and postcompetition cortisol levels (cortisol increase). Thus, athletes with higher CMJ decreases tended, significantly, to be those who experienced higher postcompetition cortisol increases. Similarly, CMJ decrease demonstrated a significant and positive correlation with race RPE; athletes who reported more exertion also manifested greater postcompetition CMJ decrease. Thereby, the CMJ seems to have a number of common factors with RPE or cortisol. With this in mind, we note that the suitability of the CMJ as an indicator of neuromuscular acute fatigue

has been studied previously.^{13,14,22,23} For example, Sánchez-Medina and González-Badillo¹⁴ found that CMJ decrease after multiple sets of full squats correlated with the decrease of speed of squats performed during the set ($r = .92$) and with postexercise lactate ($r = .97$) and ammonium levels ($r = .92$). Therefore, the results of our study are consistent with those of others in the literature that propose the CMJ as an excellent indicator of postexercise fatigue.^{13,14,24}

It was observed that athletes who competed in longer events experienced greater increases in postcompetition cortisol levels. Thus, the cortisol levels of athletes competing in 800- and 1500-m events increased by an average of 37.6%, while those competing in 3000- and 5000-m events increased by an average of 199.7%. Other studies have measured cortisol level increases after ultramarathon competitions of up to 220%,²⁵ although we are not aware of studies that compared the hormone levels of high-level runners who compete in different distances. Race distance shows no relationships with postcompetition CMJ decrease or RPE levels. Further studies are needed to learn about the different cortisol, CMJ, and RPE responses to diverse running events.

Finally, the results of our study show that both the athletes' CMJ height and their basal cortisol levels were significantly higher on the day of competition than during the baseline period. Furthermore, there was a significant and positive correlation ($r = .688$, $P < .01$)

between the increases in both the CMJ height and the basal cortisol levels on the day of competition with respect to the baseline period; the athletes who experienced larger cortisol increases also tended to attain greater CMJ height. Although chronically elevated cortisol levels display a negative relation with physical performance,^{8,26} our results suggest that there are some factors that simultaneously influence the increase in both cortisol levels and CMJ height in a competitive situation. It is well known that stressful situations such as high-level competition cause a significant increase in athletes' cortisol levels.^{27,28} It has also been documented that competition can improve physical performance by increasing variables such as enjoyment, anxiety, and effort.²⁹ However, the factors that could lead to a simultaneous increase in both cortisol levels and neuromuscular performance remain unclear. Some authors have suggested that the short-term changes in cortisol levels could have an impact on neuromuscular performance by altering the activity of the sympathetic nervous system or the muscles' contractile properties or behavior.²⁷ However, it is not clear what the mechanism for this is. Given the lack of research in this regard, further studies are needed to clarify the relationship between cortisol levels and CMJ height.

The main limitation of this study is its small sample size. Since this research concerns a largely unexplored issue (the relationship between CMJ height, cortisol levels, and RPE in high-level runners), there are still important issues to be addressed in future work. It would be interesting to have more competitors of each distance to observe whether the results of this study are repeated in different specialists. Similarly, it would be useful to know the relationship between CMJ decrease, cortisol levels, and RPE in various age groups of different sexes. In conclusion, the data from our study demonstrate the interesting relationship between CMJ height, salivary free cortisol levels, and RPE, plus further evidence is provided of the suitability of evaluating CMJ height as a means of monitoring the degree of acute fatigue of middle- and long-distance runners.

Practical Applications and Conclusions

The results of our study demonstrate the significant correlations observed between CMJ height, salivary free cortisol levels, and RPE of elite middle- and long-distance runners in high-level competition. Specifically, the decrease in postcompetition CMJ height showed high correlation with the increase in cortisol levels and RPE assessed after the competition. These data support previous findings in the literature that observed that the CMJ is a good indicator of degree of fatigue. Therefore, monitoring CMJ height before and after middle- and long-distance competitions could be a simple and practical method for evaluating athletes' acute fatigue development.

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Aportaciones del doctorando

Candidate's contributions

Teniendo en cuenta que, (1) los artículos de la presente Tesis Doctoral contienen un mismo número de autores ordenados de la misma manera en función de su contribución, y (2) que los 3 artículos que componen la presente Tesis Doctoral forman parte de un mismo estudio en el que se monitorizaron diversas variables relacionadas con el rendimiento, el grado de fatiga y la carga de entrenamiento en un grupo de corredores de alto nivel durante el transcurso de toda una temporada de entrenamiento, el autor de la presente Tesis Doctoral declara que su participación en cada uno de los artículos ha tenido la misma importancia, habiéndose dedicado a:

1. Elaborar el diseño metodológico de cada artículo.
2. Seleccionar, medir y analizar todas y cada una de las variables estudiadas en cada uno de los artículos. Para ello pasó toda una temporada de entrenamiento acompañando al entrenador y a sus atletas en sus sesiones diarias de trabajo.

Taking into account that (1) the papers which compose the present PhD Thesis contains the same number of authors, sorted in the same way, and (2) that the 3 papers which compose the present PhD Thesis are part of the same study in which several variables related to performance, fatigue and training load in high-level middle and distance runners were measured throughout a whole training season, the author of the present PhD Thesis declares that his contributions to each one of the papers have had the same relevance. Thus, he took care of:

- 1. Elaborating the methodological design of each paper.*
- 2. Selecting, measuring and analyzing every single studied variable on each study. For this, he spend a whole training season with the coach and their athletes in their daily training sessions.*

3. Redactar en su totalidad la introducción, métodos, resultados, discusión y conclusiones de cada uno de los artículos que componen la presente Tesis Doctoral.
4. Enviar cada uno de los artículos a los editores de las diversas revistas en las que dichos estudios han sido publicados o aceptados, respondiendo a los diversos comentarios que revisores y editores han ido sugiriendo durante todo el proceso editorial.

De esta forma, la aportación del autor de la presente Tesis Doctoral ha sido de máxima relevancia e imprescindible para el diseño, elaboración y publicación de los artículos.

3. Writing the introduction, methods, results, discussion and conclusions sections of each paper.

4. Sending each paper to the editors of the different journals in which the studies were published or accepted, responding to the several comments that reviewers and editors made during the publication process.

Thus, the contribution of the author of the present PhD Thesis was of maximal relevance and essential for the design, elaboration and publication of the papers.

Acerca del autor

About the author



 [twitter: @cbalsalobre](https://twitter.com/cbalsalobre)

 [ResearchGate: researchgate.net/profile/Carlos_Balsalobre-Fernandez](https://www.researchgate.net/profile/Carlos_Balsalobre-Fernandez)

 [LinkedIn: linkedin.com/in/cbalsalobre](https://www.linkedin.com/in/cbalsalobre)

 [E-mail: carlos.balsalobre@icloud.com](mailto:carlos.balsalobre@icloud.com)

Monitoring and study of the relationships between training load, force production, fatigue and performance in high-level distance runners

International PhD Thesis by Carlos Balsalobre-Fernández



*Department of Physical Education, Sport and Human Movement
Autonomous University of Madrid
Spain*

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