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FACULTAD DE HUMANIDADES Y
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DEPARTAMENTO DE DIDÁCTICA DE
LA EXPRESIÓN MUSICAL,
PLÁSTICA Y CORPORAL

TESIS DOCTORAL

RESPUESTA FISIOLÓGICA, NEUROMUSCULAR Y BIOMECÁNICA AL ENTRENAMIENTO INTERMITENTE DE ALTA INTENSIDAD EN ATLETAS DE FONDO

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A mi familia, a todos ellos

“Sólo aquellos que se arriesgan a ir muy lejos,
pueden llegar a saber lo lejos que pueden ir”
T. S. Eliot

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PHYSIOLOGICAL, NEUROMUSCULAR AND BIOMECHANICAL RESPONSES TO HIGH-INTENSITY INTERMITTENT TRAINING IN ENDURANCE RUNNERS

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CERTIFICA:

Que la Tesis Doctoral titulada “Respuesta fisiológica, neuromuscular y biomecánica al entrenamiento intermitente de alta intensidad en atletas de fondo” que presenta D. FELIPE GARCÍA PINILLOS al superior juicio del Tribunal que designe la Universidad de Jaén, ha sido realizada bajo mi dirección durante los años 2012-2016, siendo expresión de la capacidad técnica e interpretativa de su autor en condiciones tan aventajadas que le hacen merecedora del Título de Doctor, siempre y cuando así lo considere el citado Tribunal.

En Jaén, 15 de Febrero de 2016 Fdo. Pedro Ángel Latorre Román

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II. **García-Pinillos F**, Soto-Hermoso VM, Latorre-Román PA. Acute effects of extended interval training on countermovement jump and handgrip strength performance in endurance athletes: Postactivation potentiation. J Strength Cond Res. 2015; 29(1): 11-21.

III. **García-Pinillos F**, Soto-Hermoso VM, Latorre-Román PA. Acute physiological and thermoregulatory responses to extended interval training in endurance runners: Influence of athletic performance and age. J Hum Kinet. 2015; (49):129-137.

IV. **García-Pinillos F**, Soto-Hermoso VM, Latorre-Román PA. Do running kinematic characteristics change over a typical HIIT for endurance runners? J Strength Cond Res. *In press*

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IX. **García-Pinillos F**, Latorre-Román PA, Soto-Hermoso VM, Cámara-Pérez JC. A HIIT-based running plan improves athletic performance by improving muscle power. *Submitted.*

RESUMEN

Aunque no existe una definición universal, el término `entrenamiento intermitente de alta intensidad´ (HIIT) generalmente se refiere a un trabajo interválico en el que se alternan periodos de trabajo ejecutados a alta intensidad (cercana al 100% del VO_{2max}), y periodos de recuperación.

El objetivo general de esta Tesis Doctoral ha sido determinar desde una perspectiva multidisciplinar (fisiológica, neuromuscular y biomecánica) el efecto agudo de diferentes sesiones HIIT para atletas de fondo, además de comprobar las adaptaciones que genera su inclusión en el programa de entrenamiento de deportistas de resistencia.

Para satisfacer ese objetivo general se requirieron una serie de estudios que finalmente se tradujeron en nueve artículos: i) Revisión sistemática de la literatura centrada en las adaptaciones, tanto agudas como a medio-largo plazo, que producen las sesiones HIIT en atletas de fondo (Paper I); ii) Análisis de la respuesta aguda a una sesión HIIT típica para corredores de resistencia - fisiológica, neuromuscular y biomecánica – (Papers II, III y IV, respectivamente); iii) Análisis comparativo del efecto agudo entre esa estructura de sesión HIIT típica para atletas de fondo y una novedosa estructura basada en un mayor número de repeticiones más cortas (Papers V, VI y VII); iv) Efecto de un programa de entrenamiento basado en HIIT en el rendimiento atlético y en variables relacionadas con el rendimiento muscular (Papers VIII y IX).

Los principales resultados de la Tesis sugieren que: a) Atletas de fondo son capaces de mantener sus niveles de fuerza y potencia durante sesiones HIIT ejecutadas a una intensidad superior a VVO_{2max}. b) Los atletas son capaces de mantener constante su técnica de carrera durante sesiones HIIT, a pesar de los altos niveles de fatiga alcanzados. c) Dos protocolos HIIT (10x400 m vs. 40x100 m) con mismo volumen (4 km) pero diferente ritmo promedio (~3 km/h) se mostraron muy similares en términos de impacto fisiológico y metabólico. d) Un plan de carrera basado en HIIT resultó efectivo para mejorar el rendimiento atlético de triatletas, mejora que parece estar asociada a la mejoría de las prestaciones neuromusculares.

Los resultados de la presente memoria de Tesis ponen de manifiesto la importancia de este medio de entrenamiento (HIIT) para el atleta de resistencia, posibilitando una reducción del kilometraje semanal (motivo frecuente de lesión) al mismo tiempo que un incremento de la intensidad promedio de cada sesión (fuertemente asociado al rendimiento), y todo ello, sin deteriorar la respuesta neuromuscular del atleta ni la cinemática de carrera.

SUMMARY

Although there is no universal definition, high-intensity intermittent training (HIIT) generally refers to repeated short to long bouts of high-intensity exercise – performed at close to 100% VO_{2max} – interspersed with recovery periods.

The main objective of this PhD Thesis was to determine from a multidisciplinary perspective (physiological, neuromuscular and biomechanical) the acute effect of different HIIT protocols in endurance athletes, in addition to examine the adaptations that the inclusion of HIIT sessions in a training programme causes in endurance athletes.

In order to achieve that goal some studies were conducted: i) A systematic review of literature focused on both short- and long-term adaptations after HIIT protocols/interventions in endurance runners (Paper I); ii) Analysis of acute response to a typical HIIT protocol for endurance runners – physiological, neuromuscular and biomechanical – (Papers II, III and IV, respectively); iii) Analysis of acute responses to two different HIIT protocols – a typical HIIT vs. a HIIT based on shorter but faster runs – (Papers V, VI and VII); iv) Effects of a HIIT-based training programme on athletic performance and muscular performance parameters in endurance athletes (Papers VIII and IX).

The major results of this Thesis suggest that: a) Endurance runners can maintain their strength and power levels during HIIT workouts performed at intensities above VVO_{2max}. b) Despite the high levels of exhaustion reached, HIIT protocols did not consistently perturb the running kinematics of trained endurance runners. c) Two different HIIT protocols (10x400 m vs. 40x100 m), with identical volume (4 km) but different average pace (~3 km/h), showed similar data in terms of metabolic and physiological impact. d) A HIIT-based running plan was effective for improving athletic performance in triathletes; this improvement is suggested to be due to improved neuromuscular characteristics.

These findings highlight the importance of HIIT as a training method for endurance runners that leads to a reduction in weekly running distances (risk factor for lower extremity running injuries) and an increase in mean running intensity (deeply associated to running performance) without impairing the neuromuscular performance nor running kinematic characteristics.

ABREVIATURAS [ABBREVIATIONS]

AOD	Accumulated oxygen deficit
BAmm	Blood ammonia
BMI	Body mass index
BLa	Blood lactate accumulation
CA	Conditioning activity
CMJ	Countermovement jump
CoP	Center of pressure
CR	Continuous run
CT	Contact time
EE	Energy expenditure
EIT	Extended interval training
EPOC	Post-exercise oxygen consumption
FSP	Foot strike pattern
FT	Flight time
GET	Gas exchange threshold
HIIT	High-intensity intermittent training
HR	Heart rate
HS	Handgrip strength test
LTP	Lactate turn points
PAP	Postactivation potentiation
RE	Running economy
RER	Respiratory exchange ratio
RPE	Rate of perceived exertion
SIT	Sprint interval training
SJ	Squat jump
SL	Step length
SSC	Stretch-shortening cycle utilization
S20m	Maximal 20 m linear sprint
Tc	Core temperature
$\mathbf{T_{lim}}$	Time to exhaustion sustained at VO_{2max}
$\mathbf{T_{max}}$	Time for which VVO_{2max} can be maintained

VO_{2max}	Maximal oxygen uptake
V_{max}	Maximal velocity of the graded maximal test
VVO_{2max}	Velocity associated to VO_{2max}
VLTP	Velocity associated to lactate turn points
W:R ratio	Work-to-rest ratio

INTRODUCCIÓN

La moda del "running"

En las últimas décadas, la carrera recreacional ("running") ha alcanzado una enorme popularidad como una actividad física practicada por motivos muy variados (placer, salud, rendimiento deportivo…). El hecho de que no tenga límites de edad o sexo, ni esté se requieran unas demandas técnicas altas son algunas de las razones que lo convierten en una modalidad deportiva de moda. Tal y como queda patente en carreras como la Maratón de Londres o Nueva York, o en cualquier otra celebrada semanalmente en cualquier localidad, hay un interés creciente en estos corredores recreacionales de competir y participar en estos eventos. Toda esta moda del "running" ha tenido una respuesta rápida desde el mundo de la investigación en Ciencias del Deporte de modo que numerosos estudios han analizado, y lo siguen haciendo, este fenómeno deportivo y social y, consecuentemente, a día de hoy hay mucha información disponible sobre la carrera de fondo y su relación con la salud, con el rendimiento, incluyendo factores de carácter fisiológico, psicológico y sociales.

¿La carrera recreativa es realmente un deporte "seguro"?

Lo cierto es que no es una modalidad deportiva libre de lesiones. La carrera de fondo causa altas tasas de lesiones asociadas, un porcentaje estimado que varía desde el 30% al 75% por año[1–3]. Aunque comparar las tasas de lesiones aportadas por diferentes estudios es complicado por las diferencias de metodología a la hora de considerar lesiones y por las diferentes poblaciones, hay un consenso general en que la tasa es inaceptablemente alta, y aún peor, que no ha dado señales de comenzar a bajar en los últimos 30 años a pesar de los esfuerzos para intentar reducirlas. Las lesiones asociadas a la carrera de fondo son, evidentemente, multifactoriales incluyendo factores intrínsecos (masa corporal, lesiones previas, sexo, alteraciones biomecánicas) y extrínsecos (calzado, niveles de flexibilidad y fuerza, características del entrenamiento) [1–10]. Por tanto, si bien es asumido que las lesiones relacionadas con la carrera presentan una causalidad multifactorial, también se ha precisado que se asocian normalmente a errores en la prescripción del entrenamiento[4].

¿Cómo entrenan los atletas de resistencia?

Una fuerte evidencia señala que un elevado kilometraje semanal es un factor de riesgo para sufrir una lesión[1]. Sin embargo, los atletas de fondo siguen pensando “más es mejor” y continúan acumulando grandes volúmenes de entrenamiento[11]. Del mismo modo, a pesar de que un importante cuerpo de publicaciones señalan a la intensidad promedio a lo largo de una temporada como un elemento clave para optimizar el rendimiento atlético[12–16], los atletas de fondo siguen acumulando la mayor parte de su volumen de trabajo a bajas y moderadas intensidades[11].

Entrenamiento intermitente de alta intensidad en atletas de fondo

Aunque no existe una definición universal, el término `entrenamiento intermitente de alta intensidad´ (HIIT) generalmente se refiere a un trabajo interválico en el que se alternan periodos de trabajo ejecutados a alta intensidad (cercana al 100% del VO_{2max}), y periodos de recuperación. Como un medio de entrenamiento que posibilita la reducción de los volúmenes de entrenamiento semanales y un incremento en la intensidad de carrera promedio sin deteriorar el rendimiento atlético, es considerado una de las formas más efectivas para mejorar el rendimiento de los atletas[12–16]. Por tanto, dos hechos apoyan y refuerzan la inclusión de sesiones HIIT en los planes de entrenamiento de atletas de fondo: i) la acumulación de grandes volúmenes de entrenamiento semanal es un factor de riesgo para el corredor de fondo[1] y, ii) numerosos estudios destacan el rol de la intensidad promedio como elemento clave para maximizar el rendimiento atlético en atletas de fondo [12–16].

Centrándonos específicamente en corredores de resistencia, una amplia evidencia apoya y confirma los beneficios del HIIT para esta población[17–24]. Pero,

¿Qué riesgos conllevan estas sesiones HIIT en atletas de fondo?

Partiendo de que el HIIT conlleva correr más rápido, los entrenadores deben ser conscientes de los riesgos y demandas, en términos de lesiones y de prescripción de entrenamiento. Se ha constatado que el deterioro del rendimiento causado por fatiga muscular varía según algunos factores como el tipo de contracción implicada, los grupos musculares evaluados o la duración e intensidad del ejercicio[25]. Si lo comparamos con cargas de trabajo continuas, cíclicas y de inferior intensidad, una carrera intensiva requiere la activación de mayor número de unidades motoras, con mayor reclutamiento de fibras musculares oxidativas y glucolíticas, y un incremento en la intensidad de los procesos químicos en el músculo (una incrementada concentración de metabolitos inhibe la actividad de ciertas enzimas tales como sodio-potasio, calcio, y la miosina ATPasas), lo cual ejerce una influencia directa en la habilidad contráctil del músculo [26,27]. Adicionalmente, un incremento en la velocidad de Carrera ocasiona unas fuerzas de impacto mayores en miembros inferiores[28] y una mayor solicitación neuromuscular (especialmente en los isquiotibiales)[29]. El incremento de la acidez muscular y el descenso de las reservas de fosfágenos, junto con la fatiga muscular, altera la capacidad de generar fuerza muscular[30], lo que podría estar asociado a cambios en los patrones de movimiento articular[10,31–34] y cambios en la mecánica de carrera[35], a menudo asociada al riesgo de lesion[6,35]. Debido a la ausencia de estudios evaluando la prevalencia de lesiones en estas condiciones, el efecto de estas carreras de mayor intensidad en estos marcadores es todavía desconocido.

Considerando riesgos y beneficios, los entrenadores deben decidir cómo gestionar la inclusión de sesiones HIIT en los planes de entrenamiento de sus corredores, cuántas sesiones a la semana y qué duración de intervalos de trabajo o de descanso. Con estas preocupaciones en mente, decidimos revisar críticamente la literatura disponible sobre HIIT en atletas de fondo (**PAPER I**). El conocimiento sobre el efecto de cualquier sesión de entrenamiento juega un papel clave en la correcta prescripción de entrenamiento, con lo cual, una descripción profunda del impacto de las sesiones más típicas en la preparación del corredor de fondo es necesaria. Sin embargo, en este sentido la información disponible sobre HIIT en corredores de fondo es escasa. Una descripción de la respuesta metabólica y neuromuscular a sesiones de entrenamiento de atletas de resistencia facilitaría una mejor comprensión de los factores que limitan el rendimiento, y eso ayudará a la elaboración de programas de entrenamiento equilibrados y basados en la evidencia, que posibiliten mejoras en el rendimiento en carrera (**PAPERS II y III**).

En términos de prescripción de entrenamiento y prevención de lesiones sería especialmente importante, debido fundamentalmente a la ausencia de información, conocer los cambios agudos en la cinemática de carrera durante sesiones HIIT (**PAPERS IV y VII**).

Cinemática de carrera durante sesiones HIIT

El efecto de la fatiga en la cinemática de carrera ha sido extensivamente estudiado [10,31–38]. Algunos estudios previos no hallaron cambios significativos en fatiga[34,36,39], mientras otros estudios reportaron alteraciones cinemáticas después de protocolos de carrera (mayor extensión de la cadera[40], menor flexión de la rodilla en el contacto inicial[32], mayor longitud de paso con una disminución correspondiente en la cadencia[31], y cambios en el patrón de pisada[37,41]). Sin embargo, la mayoría de estos estudios fueron desarrollados en condiciones de laboratorio y con los atletas ejecutando carreras prolongadas en tapiz rodante[10,31,32], o protocolos hasta la fatiga en tapiz rodante [30,33,36]. Solo unos pocos estudios han sido desarrollados en condiciones reales[37–39], aunque todos ellos se centraron en carreras de larga distancia. Si nos centramos en HIIT, la información disponible sobre alteraciones cinemáticas asociadas, es muy limitada. De todos los estudios mencionados, únicamente dos trabajos[34,42] evaluaron los cambios cinemáticos durante protocolos HIIT. Ambos concluyeron en la misma línea, sesiones HIIT con periodos de trabajo entre 1-2 min y ejecutados a intensidad cercana al 100% VO_{2max}, no deterioraron consistentemente la cinemática de carrera de los atletas de fondo. No obstante, quedaría por determinar si un cambio en la velocidad promedio del protocolo conllevaría diferentes alteraciones en la cinemática de carrera.

¿Cómo pueden los corredores de resistencia insertar HIIT en sus programas de entrenamiento?

Muchas variables pueden ser manipuladas para prescribir HIIT, y entre ellas, la intensidad y la duración de los intervalos de trabajo y de descanso parecen ser los elementos más influyentes[15,16,43]. Por tanto, el número de series y de intervalos, y la duración e intensidad de intervalos de trabajo y descanso, determinan el trabajo total ejecutado. Adicionalmente, la manipulación de una variable de manera aislada tiene un impacto directo en la respuesta fisiológica, cardiopulmonar e incluso neuromuscular.

Cuando más de una variable es manipulada al mismo tiempo, las respuestas son aún más difíciles de predecir debido a que todos los factores están inter-relacionados, dificultando el consenso en torno a qué combinación trabajo-descanso es más efectiva, si es que la hubiera, para permitir al atleta pasar más tiempo a intensidades cercanas al VVO_{2max} al mismo tiempo que "controlamos" el nivel de implicación anaeróbica[13] y la carga neuromuscular[14].

Entonces, ¿intervalos de trabajo más cortos e intensos?

Los entrenadores se plantean si ería más efectivo ejecutar un mayor número de series cortas o, por el contrario, un menor número de series más largas durante una sesión HIIT. Parece evidente que cambios en la longitud de los esfuerzos y recuperaciones durante HIIT (carga de entrenamiento en términos de intensidad, volumen y densidad) retará a los sistemas metabólicos y neuromuscular a diferente nivel [15,16,42]. Vuorimaa et al. [42] comparó el estrés fisiológico y el rendimiento muscular de los atletas durante dos sesiones HIIT a velocidad asociada al VVO2max: 14 series de 60 s separadas por 60 s descanso, y 7 series de 120 s con 120 s de recuperación; sin embargo, ambos protocolos tuvieron un diferente impacto fisiológico. Por tanto, la clave para atletas y entrenadores es si para un mismo volumen de entrenamiento es posible incrementar el ritmo promedio sin deteriorar el impacto neuromuscular y fisiológico (**PAPERS V, VI y VII**).

HIIT en programas de entrenamiento para atletas de fondo

El conocimiento sobre los cambios, tanto agudos como adaptaciones a largo plazo, inducidos por protocolos HIIT en atletas de fondo juegan un rol clave en el proceso de prescripción de entrenamiento. El protocolo HIIT está bien documentado[16,44], y varios tipos de programas HIIT han sido mostrados para mejorar el rendimiento aeróbico en corredores[17–24]. Sin embargo, a pesar de los beneficios reportados por el entrenamiento de alta intensidad, los atletas de resistencia continúan entrenando mayoritariamente a baja intensidad[11] por lo que más evidencia es necesitada para "convencer" a atletas y entrenadores de la importancia del HIIT para atletas de fondo (**PAPERS VIII y IX**).

El mecanismo preciso por el cual HIIT puede mejorar el rendimiento aeróbico sigue sin ser determinado. Las potenciales adaptaciones que podrían contribuir a la mejora en el rendimiento aeróbico con programas HIIT incluyen la mejora de la habilidad del músculo esquelético para taponar los iones de hidrógeno[45], además de un incremento en la bomba sodio/potasio[17], capacidad anaeróbica[46] y activación de unidades motoras[47,48].

Así que, ¿Por qué mejora el rendimiento aeróbico cuando incrementa la intensidad promedio de los entrenamientos?

A pesar de las diferencias en los programas de entrenamiento conducidos por los estudios que han ejecutado rutinas basadas en HIIT con atletas de resistencia[17–24], todos coinciden en que el rendimiento atlético mejora tras una intervención HIIT. Por tanto, para responder a esa cuestión, más investigaciones centradas en las adaptaciones neuromusculares y fisiológicas a largo plazo a intervenciones HIIT, son necesitadas. La importancia de las características neuromusculares en la economía de carrera y, consecuentemente, en el rendimiento en carrera, ha sido previamente establecido[49,50]. La evaluación de parámetros neuromusculares ha alcanzado una importante dimensión para atletas de fondo y entrenadores. Mientras algunos test de salto son comúnmente ejecutados para evaluar tanto el efecto agudo de una sesión en variables neuromuscylares[42] como para valorar el efecto de un programa de entrenamiento en la potencia de las miembros inferiores[50,51], parámetros relacionados con la utilización y eficiencia del ciclo estiramiento-acortamiento (CEA), han sido utilizados para monitorizar adaptaciones al entrenamiento a lo largo de una temporada[52], y han sido asociadas a mejoras en el rendimiento, prevención de lesiones y mecanismos de fatiga[53].

Del mismo modo, la influencia del peso corporal y del estado nutricional en la economía de carrera y, por tanto, en el rendimiento atlético, ha sido previamente establecida[54]. Algunos estudios previos[55] han reconocido el potencial del HIIT para reducen la masa grasa y controlar el peso en personas con sobrepeso. Sin embargo, en lo que a poblaciones atléticas se refiere, más investigaciones son claramente necesitadas, con atletas y entrenadores preguntándose si la mayor intensidad propia de sesiones HIIT compensa el reducido volumen en términos de gasto energético total y, por tanto, si una importante reducción del volumen de entrenamiento conllevará cambios en parámetros relacionados con la composición corporal a pesar de una mayor intensidad, o no.

INTRODUCTION

Running, a fashionable sport

In the last decades, running has gained increasing popularity as a physical activity widely performed for leisure, the maintenance of health, sport training, or during physical fitness tests. Having no age or sex restrictions and being unburdened by technical demands are just some of the reasons that make running a fashionable sport. As the popularity of races such as the New York and London marathons show, there is a growing number of recreational runners becoming involved in competition. The increased interest in running has prompted a comparable increase in research and assessment efforts. Consequently, a lot of information has become available about running in relation to performance, and in relation to the benefits of running for health, including physiological, psychological, even social aspects.

Is running a perfectly safe exercise?

Running is not a risk-free sport. Distance running causes high rates of running injuries, variously estimated to be between 30% and 75% per year [1–3]. Although comparisons of injury rates among studies are complicated by different methods used to define and measure injuries and by differences between the populations studied, there is general agreement that running injury rates are unacceptably high, with no significant decline during the last 30 yr despite considerable efforts to reduce them. The causal bases for running injuries are obviously multifactorial and are often thought to include both intrinsic factors such as biomechanical abnormalities, previous injury, sex, and body mass index (BMI), as well as extrinsic factors such as shoes, flexibility, core strength, or the intensity duration and frequency of training [1–10]. Even though it is widely accepted that injuries in endurance runners are multifactorial, it is also well known that running-related injuries are often attributable to training errors[4].

But, how do endurance runners actually train? [11]

There is strong evidence that a greater training distance per week is a risk factor for lower extremity running injuries[1], but endurance runners keep thinking `more is better´ and thus, accumulate great volumes[11]. Likewise, despite a growing body of literature highlighting the role of mean training intensity over a season in optimising athletic performance[12–16], endurance runners continue to spend most of their time training at low intensities[11].

High-intensity intermittent training in endurance runners

Although there is no universal definition, high-intensity intermittent training (HIIT) generally refers to repeated short to long bouts of high-intensity exercise – performed at close to 100% maximal oxygen uptake (VO_{2max}) – interspersed with recovery periods. As a training method that leads to a reduction in weekly running distances and an increase in mean running intensity without impairing athletic performance, it is considered one of the most effective forms of exercise for improving the physical performance of athletes[12–16]. Therefore, two facts support and reinforce the inclusion of HIIT into running plans for endurance runners: i) a greater training distance per week in runners is a risk factor for lower extremity running injuries [1] and, ii) a growing body of literature remarks the role of mean training intensity over a season for optimising the athletic performance [12–16].

Focusing specifically on endurance runners, extensive evidence supports the benefits of fast intermittent exercises for endurance runners[17–24]. But,

What is about the risk of HIIT workouts for endurance runners?

Since HIIT results in running faster, coaches also need to be aware of the risks and demands in terms of injury management and training prescription. It has been demonstrated that the impairment of performance resulting from muscle fatigue differs according to the types of contraction involved, the muscular groups tested, or the exercise duration and intensity[25]. Compared with lower intensity cyclic workloads, intensive running requires activation of larger motor unit, with increased recruitment of fast oxidative and glycolytic muscle fibres and an increase in the intensity of chemical processes in the muscle (increased metabolite concentration inhibits the activity of certain enzymes such as sodium–potassium, calcium, and myosin ATPases), which exerts a direct influence on the contractile ability of the muscle[26,27]. Additionally, increases in running speed lead to higher impact forces being imposed on the lower limbs[28] and greater levels of neuromuscular engagement (mainly in the hamstring muscles)[29]. The concomitant increase in muscle acidity and decrease in phosphagen stores with muscle fatigue alters muscle force generation capabilities[30], which may be linked to changes in joint movement patterns[10,31–34] and running mechanics[35] often linked to running injury[6,35]. Due to a lack of studies evaluating injury occurrence, the effects of more strenuous runs on these markers are still unknown.

Having taken risks and benefits into consideration, coaches must themselves decide how to manage HIIT inclusion in running plans for endurance athletes, for example, how many sessions per week and the duration of work and relief periods or intensities. Having these concerns in mind, the authors aimed to critically revise the literature available about HIIT and endurance runners **(PAPER I)**. The knowledge about every possible effect of a particular training protocol on the athlete plays a key role in the proper training prescription, which means that a further description of the impact of most typical running exercises on endurance runners is necessary. Nevertheless, the available information about the acute impact of typical HIIT protocols on endurance runners is scarce. A description of the metabolic and neuromuscular responses to the training sessions of endurance runners may lead to a better understanding of the factors that limit performance, and this will help in the preparation of a scientifically-based and well-balanced training programme for improving running performance (**PAPERS II and III**).

In terms of injury management and training prescription would be especially important, due to the lack of information, to know the acute changes in running kinematics during HIIT workouts (**PAPERS IV and VII**).

Running kinematics during HIIT protocols

The effect of exertion on running kinematics has been extensively studied [10,31–38]. Some previous studies reported non-significant running kinematic alterations after different running exercises [34,36,39], whereas other works found fatigue-induced changes during running at kinematic level - i.e. increased hip extension [40], decreased knee flexion angle at foot strike [32], increase in step length with a corresponding decrease in cadence [31], and changes in foot strike pattern [37,41]. However, most of these studies were performed in laboratory conditions and with athletes performing prolonged treadmill runs [10,31,32], or running-induced fatigue protocol on treadmills [30,33,36]. Just a few studies have been field-based [37–39], although all of them were focused on long-distance road racing. The evidence of changes induced by intermittent running protocols is quite limited. From all these studies, only two works [34,42] assessed HIIT-induced changes to the biomechanics of running. Both agreed that HIIT sessions including runs for 1–2 min and performed at intensity close to maximal oxygen uptake (VO_{2max}), did not consistently perturb the running kinematics of trained male runners. What is still unknown is whether the difference in mean velocity between different HIIT protocols will lead to different alterations in running kinematics.

How can endurance runners insert HIIT workouts in their routines?

Many variables can be manipulated to prescribe different HIIT sessions and among them, the intensity and duration of work and relief intervals are the key influencing factors[15,16,43]. Then, the number of intervals and the number of series and between-series recovery durations and intensities determine the total work performed. Additionally, the manipulation of each variable in isolation likely has a direct impact on metabolic, cardiopulmonary and/or neuromuscular responses. When more than one variable is manipulated simultaneously, responses are more difficult to predict, since the factors are inter-related, making it unclear which combination of work-interval duration and intensity, if any, is most effective at allowing an individual to spend prolonged time at VVO_{2max} while ‘controlling’ for the level of anaerobic engagement[13] and/or neuromuscular load[14].

Then, shorter and faster intervals?

Coaches have questioned whether it would be more effective to perform a higher number of shorter runs, or a few long runs during a HIIT workout. It seems clear that changes in the length of efforts and recovery intervals during HIITs (training load in terms of intensity, volume and density) will challenge both the metabolic and the neuromuscular systems at different levels [15,16,42]. Vuorimaa et al. [42] compared the physiological strain and muscular performance of athletes during two HIIT workouts at velocities associated with maximal oxygen uptake (VO_{2max}): 14 runs of 60 seconds separated by 60 seconds of rest and 7 runs of 120 seconds interspersed with 120 seconds of rest; however, both protocols had a different physiological response. Thus, the key point for coaches and athletes is whether at the same absolute training load/volume it is possible to increase the average training pace, by modifying other variables such as intensity or the number of runs, without changing the physiological and neuromuscular impact (**PAPERS V, VI and VII**).

HIIT-based training programmes for endurance athletes

The knowledge about either the acute changes induced by HIIT protocols or the long-term adaptations induced by HIIT-based interventions in endurance runners plays a key role in the training prescription process. The HIIT protocol is well documented [16,44], and various types of HIIT programmes have been shown to improve endurance performance in runners[17–24]. However, despite the reported benefits of training at a high intensity, endurance athletes continue to train mostly at low intensities [11]; thus, more evidence is needed to “convince” coaches and athletes of the importance of HIIT for endurance performance (**PAPERS VIII and IX**).

The precise mechanisms by which HIIT can improve endurance performance remain undetermined. Potential adaptations that may contribute to the improvement in endurance performance following HIIT include the increased ability of skeletal muscle to buffer hydrogen ions [45], as well as increased Na+/K+ pump capacity [17], anaerobic capacity [46] and/or motor unit activation [47,48]. So,

Why does endurance performance improve when running intensities during workouts are increased?

Despite differences in training programmes conducted by these studies performing HIIT-based routines with endurance athletes [17–24], all agree that athletic performance improved after HIIT intervention. Therefore, in order to answer the above question, more investigations focused on long-term neuromuscular and physiological adaptations to HIIT interventions are needed. It is well established the importance of neuromuscular characteristics in determining running economy and, thereby, running performance [49,50]. Evaluation of neuromuscular parameters has become an important consideration for endurance athletes and coaches. Whilst jumping tests are commonly used to assess both the acute effects of workouts at the neuromuscular level [42] and the effectiveness of training protocols on lower body power [50,51], parameters related with stretch-shortening cycle utilization (SSC), have been used for monitoring training adaptations over a sports season [52] and have been associated with performance enhancement, injury prevention and fatigue mechanisms [53].

Likewise, it is widely accepted the influence of body mass and nutritional status on running economy and, thereby, running performance [54]. Some previous studies have recognised the potential of this training method as an effective protocol for reducing fat of non-athletic populations. However, according to trained populations, more research is clearly needed and coaches are still wondering whether a higher intensity allows HIIT to compensate for the reduced total volume in terms of total energy expenditure and, therefore, whether an important reduction in training volume will lead to changes in body composition parameters despite a higher training intensity or not.

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OBJETIVOS

General:

Por un lado, determinar el efecto agudo de una sesión típica de trabajo intermitente de alta intensidad para atletas de fondo a nivel neuromuscular, fisiológico y biomecánico, y compararlo a un HIIT con una estructura que posibilita una mayor intensidad promedio. Por otro lado, basándonos en las conclusiones reportadas por los estudios anteriores, desarrollar un programa de entrenamiento basado en HIIT y comprobar su eficacia.

Específicos:

- Revisar y analizar críticamente la literatura disponible para determinar el efecto, a corto y largo plazo, del HIIT en atletas de fondo no profesionales (Paper I).
- Analizar la respuesta aguda neuromuscular a una sesión HIIT común para atletas de fondo (Paper II).
- Describir el impacto agudo de una sesión HIIT en variables fisiológicas y en la capacidad termorreguladora de atletas de fondo, además de determinar la influencia del nivel atlético y de la edad en dicha respuesta (Paper III).
- Evaluar la cinemática de la carrera durante una sesión HIIT típicamente ejecutada por atletas de fondo, comprobando el efecto de la fatiga acumulada (Paper IV).
- Comparar el efecto agudo de dos protocolos HIIT en variables fisiológicas y de rendimiento muscular en atletas de resistencia, determinando si una sesión HIIT tradicionalmente ejecutada (10×400m) tiene un impacto similar a otra (40×100m) que supone un incremento de la intensidad promedio del entrenamiento a pesar de mantener el volumen total (Paper V).
- Describir el efecto agudo de dos sesiones HIIT en el control postural, salto vertical y utilización del ciclo estiramiento-acortamiento en atletas de fondo, además de comparar los cambios inducidos por ambos protocolos en dichas variables (Paper VI).
- Evaluar la cinemática de carrera de atletas de fondo durante dos protocolos HIIT diferentes (10x400m vs. 40x100m), además de determinar el efecto de la fatiga inducida por ambos protocolos en las mencionadas variables cinemáticas (Paper VII).

- Determinar el efecto de cinco semanas de un plan de carrera basado en HIIT en el rendimiento atlético en una prueba específica, y comparar las respuestas fisiológicas y neuromusculares durante un triatlón distancia esprint, antes y después del periodo de intervención (Paper VIII and IX).

AIMS

Overall:

On the one hand, to determine the acute effect of a typical HIIT workout for endurance runners at neuromuscular, physiological and biomechanical level, and to compare it with a HIIT that involves faster runs and a greater average running pace. On the other hand, to determine the effectiveness of a training programme based on findings reported by the previous studies.

Specifics:

- To critically analyse the literature to determine how HIIT affects non-elite endurance runners in the short- and long-term (Paper I).
- To analyse the acute neuromuscular response to a common HIIT protocol for endurance runners (Paper II).
- To describe the acute impact of a HIIT workout on physiological and thermoregulatory levels, as well as to determine the influence of athletic performance and age effect on the aforementioned response in endurance runners (Paper III).
- To evaluate running kinematic characteristics during early and late stages of an actual and common HIIT for endurance runners (Paper IV).
- To compare the physiological strain and muscular performance parameters of endurance runners during two HIIT workouts by determining whether a typical HIIT for endurance runners (10×400m) leads to a similar impact as a HIIT protocol (40×100m) that increases the average training pace despite maintaining the same training volume (Paper V).
- To describe the acute effects of two different HIIT protocols on postural control, vertical jumping ability, and stretch-shortening cycle utilisation, and to compare the changes induced by both protocols in those variables in endurance runners (Paper VI).
- To evaluate running kinematic characteristics during early and late stages of two HIIT protocols for endurance runners (10x400m vs. 40x100m) (Paper VII).
- To examine the effect of a five-week HIIT-based running plan on athletic performance, and to compare the physiological and neuromuscular responses

during a sprint-distance triathlon before and after the HIIT period (Paper VIII and IX).

MATERIAL Y MÉTODOS

La sección de material y métodos de la presente memoria de Tesis se resume en la siguiente tabla que incluye la información metodológica más relevante de los artículos que componen la memoria de Tesis (Tabla 1):

Tabla 1. Tabla resumen de las metodologías utilizadas en los diferentes artículos que componen esta Tesis Doctoral.

Artículo	Diseño de estudio	Participantes	Protocolo ejecutado	Variables medidas
I. How does HIIT affect to non-elite endurance runners? Acute and chronic adaptations: A systematic review	Revisión sistemática	▪ La búsqueda se efectuó en bases de datos electrónicas, desde Enero del 2000 a Octubre de 2015 ▪ Palabras clave: HIIT, ejercicio intermitente de alta intensidad, carrera interválica, SIT, corredores de resistencia, atletas ▪ Estudios se incluyeron en esta revisión si investigaron HIIT en corredores de resistencia de nivel no élite. Estudios de intervención fueron evaluados mediante la escala Physiotherapy Evidence Database (PEDro). Finalmente 23 estudios cumplieron los criterios de inclusión		
II. Acute effects of EIT on CMJ and HS performance in endurance athletes: Postactivation potentiation	Corte transversal	*n* = 30 hombres	4 x 3 x 400 m: 1 min recuperación pasiva entre series, y 3 entre bloques	▪ Respuesta fisiológica (Lac, FC) y neuromuscular (CMJ y dinamometría manual) ▪ Rendimiento atlético (ritmo promedio en el HIIT)
III. Acute physiological and thermoregulatory responses to EIT in endurance runners: Influence of athletic performance and age	Corte transversal	*n* = 31 hombres	Idéntico al artículo II	▪ Respuesta fisiológica (Lac, FC y T ºC) ▪ Rendimiento atlético (ritmo promedio en el HIIT)
IV. Do running kinematic characteristics change over a typical HIIT for endurance runners?	Corte transversal	*n* = 28 hombres	Idéntico a los artículos II y III	▪ Variables cinemáticas desde plano lateral, medidas en la primera y última serie del protocolo (espacio-temporales, ángulos relativos y tipo de contacto inicial con la superficie) ▪ Variables fisiológicas, RPE y rendimiento atlético

Tabla 1. (cont.)

Artículo	Diseño de studio	Participantes	Protocolo ejecutado	Variables medidas
V. Acute metabolic, physiological and neuromuscular responses to two HIIT protocols in endurance runners.	Medidas repetidas	*n*=18(16H, 2M)	• HIIT: 10 × 400 m, 90-120 s recuperación pasiva • HIIT: 40×100 m, 25-30 s recuperación pasiva *Intensidad >VVO_{2max}	▪ Respuesta fisiológica (Lac y amonio) y neuromuscular (CMJ y dinamometría) ▪ Respuesta cardiovascular ▪ Rendimiento atlético (ritmo promedio en HIITs)
VI. Changes in balance ability, power output, and SSC utilisation after two HIIT protocols in endurance runners	Medidas repetidas	Idéntico al artículo V		▪ Respuesta fisiológica (Lac y FC) y neuromuscular (control postural, test de salto, CEA) ▪ Rendimiento atlético (ritmo promedio en HIITs)
VII. Kinematic alterations after two HIIT protocols in runners	Medidas repetidas	Idéntico a artículos V y VI		▪ Cinemática de la Carrera desde plano sagital en la primera y última serie de cada HIIT (espacio-temporales, ángulos relativos y tipo de contacto inicial con la superficie) ▪ Variables fisiológicas, RPE y rendimiento atlético
VIII. A HIIT-based running programme allows triathletes to reduce weekly running distances without impairing muscular performance and body composition	Diseño longitudinal (pre-post) con 2 grupos (EG and CG)	*n* = 13 hombres Grupo HIIT (EG, n=7) Grupo control (CG, n=6)	• CG→ mantuvieron sus rutinas de entrenamiento • EG→ mantuvieron rutinas de ciclismo y natación, y modificaron su plan de carrera (basado en HIIT)	▪ Composición corporal, salto vertical, CEA y rendimiento en sprint fueron ejecutados antes y después de la intervención (pre- y post-test)

Tabla 1. (cont.)

Artículo	Diseño de estudio	Participantes	Protocolo ejecutado	Variables medidas
IX. A HIIT-based running plan improves athletic performance by improving muscle power	Idéntico al artículo VIII			▪ Rendimiento en un triatlón sprint antes y después de la intervención (pre- y post-test) ▪ Respuesta fisiológica (FC, Lac y RPE) y neuromuscular (test de salto) a la competición

CEA: ciclo estiramiento-acortamiento; CMJ: salto con contramovimiento; FC: frecuencia cardíaca; HIIT: entrenamiento intermitente de alta intensidad; Lac: acumulación de lactato; RPE: percepción subjetiva del esfuerzo; TºC: Temperatura corporal; VO_{2max}: consumo máximo de oxígeno; VVO_{2max}: velocidad asociada al VO_{2ma}

MATERIAL AND METHODS

Material and methods section is summarised in the next table (Table 1), including the more important information of every paper that takes part of this PhD Thesis:

Table 1. Summary table of the methodology used in the current Thesis.

Paper	Study design	Participants	Exercise protocol	Outcome measures
I. How does HIIT affect to non-elite endurance runners? Acute and chronic adaptations: A systematic review	Systematic review	▪ Electronic databases were searched for literature dating from January 2000–October 2015 ▪ Key words: HIIT, high-intensity interval exercise, interval running, SIT, endurance runners, long distance runners ▪ Studies were included if they investigated HIIT in non-elite endurance runners. Longitudinal studies were evaluated using the Physiotherapy Evidence Database (PEDro) scale. Twenty-three studies met the inclusionary criteria for review		
II. Acute effects of EIT on CMJ and HS performance in endurance athletes: Postactivation potentiation	Unilateral cross-over.	*n* = 30 males 28 ± 8 years VO_{2max} 58±4 ml/kg/min	4 x 3 x 400 m: 4 sets of 3 runs, 1-min passive recovery between runs, and 3-min between sets	▪ The physiological (BLa and HR), and neuromuscular responses (CMJ and HS) were controlled. ▪ The athletic performance was also assessed (running pace)
III. Acute physiological and thermoregulatory responses to EIT in endurance runners: Influence of athletic performance and age	Unilateral cross-over.	*n* = 31 males 27 ± 7 years VO_{2max} 60±3 ml/kg/min	Identical to paper II	▪ The physiological response (BLa, HR and Tc) was controlled. ▪ The athletic performance was also assessed (running pace)
IV. Do running kinematic characteristics change over a typical HIIT for endurance runners?	Unilateral cross-over.	*n* = 28 males 38.2 ± 8 years VO_{2max} 58±4 ml/kg/min	Identical to papers II and III	▪ Sagittal-plane kinematics at the 1st and 12th run were measured (spatial-temporal variables, joint angles and FSP) ▪ Physiological variables, RPE and athletic performance were also recorded

Table 1. (cont.)

Paper	Study design	Participants	Exercise protocol	Outcome measures
V. Acute metabolic, physiological and neuromuscular responses to two HIIT protocols in endurance runners.	Repeated measures	*n*=18(16M, 2F) 30.9 ± 11 years VVO_{2max} 17±1 km/h	• HIIT: 10 × 400 m, 90-120 s passive recovery between runs • HIIT: 40×100 m, 25-30 s passive recovery between runs *Intensity >VVO_{2max}	▪ The physiological (BLa and BAmm) and the neuromuscular (CMJ and HS) responses were controlled ▪ Cardiovascular response was monitored ▪ The athletic performance was also assessed (running pace)
VI. Changes in balance ability, power output, and SSC utilisation after two HIIT protocols in endurance runners	Repeated measures	Identical to papers V		▪ The physiological (BLa and HR) and the neuromuscular (postural control, jumping test, SSC) responses were controlled ▪ The athletic performance was also assessed (running pace)
VII. Kinematic alterations after two HIIT protocols in runners	Repeated measures	Identical to papers V and VI		▪ Sagittal-plane kinematics at the first and last run of every HIIT were measured (spatial-temporal variables, joint angles and FSP) ▪ Physiological variables, RPE and athletic performance were also recorded
VIII. A HIIT-based running programme allows triathletes to reduce weekly running distances without impairing muscular performance and body composition	Parallel two-group (EG and CG), longitudinal (pre, post) design	*n* = 13 males HIIT group (EG, n=7) Control group (CG, n=6)	• CG→ maintained their normal training routines • EG→ maintained only their swimming and cycling routines and modified their running routine (HIIT-based)	▪ Body composition, vertical jump, SSC utilization and sprint ability were performed before and after the HIIT intervention (pre- and post-test)

Table 1. (cont.)

Paper	Study design	Participants	Exercise protocol	Outcome measures
IX. A HIIT-based running plan improves athletic performance by improving muscle power	Identical to paper VIII			▪ Performance in sprint-distance triathlon before and after the intervention (pre- and post-test) were registered ▪ The physiological (HR, BLa and RPE) and neuromuscular (jumping test) responses to the race was measured

BMI: body mass index; BLa: blood lactate accumulation; HR: heart rate; Tc: Core temperature; VO_{2max}: maximal oxygen uptake; HIIT: high-intensity intermittent training; RPE: rate of perceived exertion; VVO_{2max}: velocity associated to VO_{2max}; CMJ: countemovement jump; HS: handgrip strength test; SJ: squat jump.

RESULTADOS

Los resultados se presentan en la forma en que han sido previamente publicados/sometidos en revistas científicas. Adicionalmente, se ofrece una tabla resumen de los principales resultados obtenidos en cada uno de los estudio en la siguiente tabla (Tabla 2):

Tabla 2. Resumen de los resultados obtenidos en los diferentes artículos que componen la presente Tesis.

Artículo	Resultados
I. How does HIIT affect to non-elite endurance runners? Acute and chronic adaptations: A systematic review	23 estudios cumplieron los criterios de inclusión. Los resultados se presentan en dos partes: estudios de corte transversal (n=15) y estudios longitudinales (n=8). En los 15 estudios tranversales analizados, corredores de resistencia recreacionales ejecutaron, al menos un HIIT y su efecto agudo en variables fisiológicas, neuromusculares, metabólicas y/o biomecánicas fue analizado. Los 8 estudios de intervención duraron, al menos, 4 semanas, con 10 para el más largo, e incluyeron 2-4 sesiones HIIT por semana. La mayoría de estos estudios combinaron HIIT y sesiones de carrera continua, solo 2 estudios ejecutaron exclusivamente HIIT.
II. Acute effects of EIT on CMJ and HS performance in endurance athletes: Postactivation potentiation	ANOVA reveló una mejora significativa en CMJ ($p<0.001$) a lo largo del protocolo. El análisis de cluster agrupó a los atletas en responders group (RG, n=17) o no-responders (NRG, n=13), en relación a si experimentaron potenciación o no (cambio en CMJ entre reposo y post-ejercicio). RG obtuvo mejoras significativas ($p<0.05$) en CMJ, dinamometría y T400m
III. Acute physiological and thermoregulatory responses to EIT in endurance runners: Influence of athletic performance and age	Análisis de medidas repetidas reveló diferencias significativas a lo largo del HIIT en las variables analizadas. Un análisis de cluster agrupó a los atletas en relación al rendimiento (T400m) distinguiendo entre atletas de mayor y menor nivel. Otro cluster fue ejecutado en relación a la edad, obteniendo un grupo de mayor y otro de menor edad promedio. ANOVA entre grupos creados reveló diferencias no significativas en la respuesta al HIIT.
IV. Do running kinematic characteristics change over a typical HIIT for endurance runners?	No se hallaron cambios significativos en las variables cinemáticas a lo largo del HIIT. Se ejecutaron dos análisis de cluster, uno en relación al ritmo promedio (Rápidos vs. Lentos), otro en relación al nivel de fatiga acumulado (Fatigados [EG] vs. No-fatigados [NEG]). No hubo diferencias entre grupos en la primera serie del HIIT (nivel basal). En cuanto a los cambios inducidos por el protocolo, se hallaron diferencias significativas ($p < 0.05$) entre Rápidos vs. Lentos en el momento de impulsión (cadera y rodilla), y en NEG con mayor extensión de la cadera en el momento de impulsión (+ 4.3º) y una mayor flexión de la rodilla de la pierna en vuelo en el momento de impulsión (- 5.2º)

Tabla 2. (cont).

Artículo	Resultados
V. Acute metabolic, physiological and neuromuscular responses to two HIIT protocols in endurance runners.	No se hallaron diferencias significativas entre ambos protocolos en Lac, amonio, FC_{pico}, ni dinamometría. Diferencias significativas se encontraron en los cambios inducidos por la fatiga durante ambos protocolos en CMJ (−0.36 cm en 40×100m; +1.48 cm en 10×400m), y en ritmo promedio ($P<0.001$) que fue más rápido durante 40×100m.
VI. Changes in balance ability, power output, and SSC utilisation after two HIIT protocols in endurance runners	Un análisis de medidas repetidas reveló una mejora significativa en CMJ y SJ durante 10×400 m ($p<0.05$), mientras no se hallaron cambios durante el 40×100m. Índices relacionados con CEA no experimentaron cambios durante ningún protocolo. El control postural no se alteró durante 40x100m, mientras se deterioró durante 10x400m ($p<0.05$)
VII. Kinematic alterations after two HIIT protocols in runners	Altos niveles de fatiga fueron alcanzados durante ambos HIIT. Una comparación de medias intra-protocolo (primera vs. última) no reveló cambios significativos ($P \geq 0.05$) en cinemática de carrera durante ambos HIIT. La comparación entre la primera serie de ambos protocolos (entre-protocolos) reveló el efecto de la velocidad de carrera en la cinemática (+2.4 kmh durante 40x100m: ↓tiempo de contacto y vuelo, ↑longitud de paso; ↑flexión de cadera y ↓flexión tobillo al contacto inicial; ↓flexión de rodilla y tobillo en amortiguación; ↑extensión cadera al despegue)
VIII. A HIIT-based running programme allows triathletes to reduce weekly running distances without impairing muscular performance and body composition	Diferencias no significativas ($P \geq 0.05$) entre grupos fueron encontradas al pre-test. Al posttest, el GE obtuvo mejor rendimiento en CMJ ($p = 0.005$, $ES > 0.7$), un mayor SSC ($p = 0.017$, $ES > 0.7$), y un mejor rendimiento en esprint ($p = 0.001$, $ES > 0.7$). Composición corporal no cambió en ninguno de los grupos ($p \geq 0.05$, $ES < 0.4$)
IX. A HIIT-based running plan improves athletic performance by improving muscle power	Diferencias no significativas ($P \geq 0.05$) entre grupos fueron encontradas al pre-test. Tras la intervención, el GE mejoró significativamente el rendimiento en salto vertical (~5-8%, $P=0.05$), en ciclismo ($P=0.046$) y en carrera ($P=0.018$) durante la competición. El GC permaneció sin cambios ($P \geq 0.05$). No se observaron cambios ($P \geq 0.05$) en RPE, FC_{media} y Lac. Análisis de regresión lineal mostró que ΔCMJ predecía el $\Delta T_{carrera}$ ($R^2=0.559$; $P=0.008$) y ΔT_{total} ($R^2=0.391$; $P=0.048$)

CMJ: salto con contramovimiento; FC: frecuencia cardíaca; GE: grupo experimental; GC: grupo control; HIIT: entrenamiento intermitente de alta intensidad; Lac: acumulación de lactato; RPE: percepción subjetiva del esfuerzo; TºC: Temperatura corporal; Δ: incremento (pre- vs. post-test)

RESULTS

The results section is presented in the same way that have been previously published or submitted to scientific journals. Additionally, the main results of every paper are presented in the next table (Table 2).

Table 2. Summary table of the results obtained in the current Thesis.

Paper	Results
I. How does HIIT affect to non-elite endurance runners? Acute and chronic adaptations: A systematic review	Twenty-three studies met the inclusionary criteria for review. The results are presented in two parts: cross-sectional (n=15) and intervention studies (n=8). In the 15 cross-sectional studies selected, non-elite endurance runners performed at least one HIIT protocol and the acute impact on physiological, neuromuscular, metabolic and/or biomechanical variables were assessed. Intervention studies lasted a minimum of four weeks, with ten weeks being the longest intervention period, and included two to four HIIT sessions per week. Most of these studies combined HIIT sessions with continuous run (CR) sessions; two works performed HIIT exclusively.
II. Acute effects of EIT on CMJ and HS performance in endurance athletes: Postactivation potentiation	ANOVA revealed a significant improvement in CMJ ($p<0.001$) throughout the protocol. Cluster analysis grouped according to whether potentiation was experienced (RG, responders group, n=17) or not (NRG, non-responders group, n=13) in relation to CMJ change from rest to fatigued condition at the end of activity. RG significantly improved ($p<0.05$) the performance in CMJ, handgrip strength and 400m time.
III. Acute physiological and thermoregulatory responses to EIT in endurance runners: Influence of athletic performance and age	A repeated measures analysis revealed significant differences throughout EIT in examined variables. Cluster analysis grouped according to the average performance in 400 m runs led to distinguish between athletes with a higher and lower sports level. Cluster analysis was also performed according to age, obtaining an older group and a younger group
IV. Do running kinematic characteristics change over a typical HIIT for endurance runners?	No significant changes ($p \geq 0.05$) in kinematic variables were found during the HIIT session. Two cluster analyses were performed, according to the average running pace – Faster vs. Slower, and according to exhaustion level reached – exhausted vs. non-exhausted group (EG and NEG). At 1st run, no significant differences were found between-groups. As for the changes induced by the running protocol, significant differences ($p < 0.05$) were found between faster and slower athletes at toe-off in θHip and θKnee, while some changes were found in NEG in θHip during toe-off (+ 4.3º) and θKnee at toe-off (- 5.2º) during swing.

Table 2. (cont).

Paper	Results
V. Acute metabolic, physiological and neuromuscular responses to two HIIT protocols in endurance runners.	No significant differences between HIITs were found for BLa_1min post-test, BAmm, HS and HRpeak. Significant differences were found in fatigue-induced changes in CMJ performance (−0.36 cm in 40×100m; +1.48 cm in 10×400m), and in average pace (P<0.001) which was faster during the 40×100m.
VI. Changes in balance ability, power output, and SSC utilisation after two HIIT protocols in endurance runners	Repeated measures analysis revealed a significant improvement in CMJ and SJ during 10×400m (p<0.05), whilst no significant changes were observed during 40×100m. Indexes related to SSC did not experience significant changes during any of the protocols. As for postural control, no significant changes were observed in the 40×100m protocol, whilst significant impairments were observed during the 10×400m protocol (p<0.05).
VII. Kinematic alterations after two HIIT protocols in runners	High levels of exhaustion were reached by the athletes during both workouts. A within-protocol paired t-test (first vs. last run) revealed no significant changes (*P*≥0.05) in kinematic variables during any of the HIIT sessions. A between-protocol comparison with the first run of each protocol revealed the effect of running speed on kinematics (+2.4 kmh during 40x100m: ↓contact and flight time, and ↑step length; ↑hip flexion and ↓ankle flexion at initial contact; ↓knee and ankle flexion at mid-stance; ↑hip extension at toe-off).
VIII. A HIIT-based running programme allows triathletes to reduce running distances without impairing muscular performance and body composition	No significant differences between groups were found at pretest. At posttest, the EG obtained higher values in countermovement jump (p=0.005, ES>0.7) and SSC (p=0.017, ES>0.7), with lower times (p=0.001, ES>0.7) in sprint. Body composition parameters remained unchanged in both groups (p≥0.05, ES<0.4)
IX. A HIIT-based running plan improves athletic performance by improving muscle power	No differences between groups were found at pre-test. After the HIIT period, the EG significantly improved jumping performance (~5-8%, *P*=0.05), cycling performance (*P*=0.046) and running time (*P*=0.018) during the competition. The CG remained unchanged (*P*≥0.05). No changes (*P*≥0.05) were observed in RPE, HR_{mean} and BLa. A linear regression analysis showed that ΔCMJ predicted ΔRu_{time} ($R^2=0.559$; $P=0.008$) and $\Delta Overall\_{time}$ ($R^2=0.391$; $P=0.048$)

CMJ: countermovement jump; HR: heart rate; EG: experimental group; CG: control group; HIIT: high-intensity intermittent training; BLa: lactate accumulation; RPE: rate of perceived exertion; Tc: core temperature; Δ: increases (pre- vs. post-test)

1. HIGH-INTENSITY INTERMITTENT TRAINING AND ENDURANCE RUNNERS

(PAPER I)

How does high-intensity intermittent training affect to non-elite endurance runners? Acute and chronic adaptations: A systematic review

García-Pinillos Felipe, Soto-Hermoso Víctor M, Latorre-Román Pedro Á.

Submitted

HOW DOES HIGH-INTENSITY INTERMITTENT TRAINING AFFECT TO NON-ELITE ENDURANCE RUNNERS? ACUTE AND CHRONIC ADAPTATIONS: A SYSTEMATIC REVIEW

RUNNING HEAD: HIIT AND ENDURANCE RUNNERS

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ABSTRACT

Objective: This systematic review aimed to critically analyse the literature to determine how high-intensity intermittent training (HIIT) affects non-elite endurance runners in the short- and long-term.

Methods: Electronic databases were searched for literature dating from January 2000–October 2015. The search was conducted using the key words ‘‘high-intensity intermittent training’’ OR ‘‘high-intensity interval exercise’’ OR ‘‘interval running’’ OR ‘‘sprint interval training’’ AND ‘‘endurance runners’’ OR ‘‘long distance runners’’. A systematic approach was used to evaluate the 783 articles identified for initial review. Studies were included if they investigated HIIT in non-elite endurance runners. Longitudinal studies were evaluated using the Physiotherapy Evidence Database (PEDro) scale.

Results: Twenty-three studies met the inclusionary criteria for review. The results are presented in two parts: cross-sectional (n=15) and intervention studies (n=8). In the 15 cross-sectional studies selected, non-elite endurance runners performed at least one HIIT protocol and the acute impact on physiological, neuromuscular, metabolic and/or biomechanical variables were assessed. Intervention studies lasted a minimum of four weeks, with ten weeks being the longest intervention period, and included two to four HIIT sessions per week. Most of these studies combined HIIT sessions with continuous run (CR) sessions; two works performed HIIT exclusively.

Conclusions: HIIT-based running plans (two to three HIIT sessions per week, combining HIIT and CR runs) show athletic performance improvements in endurance runners by improving VO2max and RE along with muscular and metabolic adaptations. In order to maximise the adaptations to training, both HIIT and CR must be part of training programmes for endurance runners.

Keywords: high-intensity training; intermittent exercises; interval running; long-distance runners

1. INTRODUCTION

Having no age or sex restrictions and being unburdened by technical demands are just some of the reasons that make running a fashionable sport. As the popularity of races such as the New York and London marathons show, there is a growing number of recreational runners becoming involved in competition. Nevertheless, running is not a risk-free sport. The incidence of running-related injuries on an annual basis is high, occurring in 40–50% of runners[1]. Even though it is widely accepted that injuries in endurance runners are multifactorial, it is also well known that running-related injuries are often attributable to training errors[2]. There is strong evidence that a greater training distance per week is a risk factor for lower extremity running injuries[3], but endurance runners keep thinking `more is better´ and thus, accumulate great volumes[4]. Likewise, despite a growing body of literature highlighting the role of mean training intensity over a season in optimising athletic performance[5–9], endurance runners continue to spend most of their time training at low intensities[4].

Although there is no universal definition, high-intensity intermittent training (HIIT) generally refers to repeated short to long bouts of high-intensity exercise – performed at close to 100% maximal oxygen uptake (VO_{2max}) – interspersed with recovery periods. As a training method that leads to a reduction in weekly running distances and an increase in mean running intensity without impairing athletic performance, it is considered one of the most effective forms of exercise for improving the physical performance of athletes[5–9].

Focusing specifically on endurance runners, extensive evidence supports the benefits of fast intermittent exercises for endurance runners[10–17]. However, since HIIT results in running faster, coaches also need to be aware of the risks and demands in terms of injury management and training prescription. Compared with lower intensity cyclic workloads, intensive running requires activation of larger motor unit, with increased recruitment of fast oxidative and glycolytic muscle fibres and an increase in the intensity of chemical processes in the muscle (increased metabolite concentration inhibits the activity of certain enzymes such as sodium–potassium, calcium, and myosin ATPases), which exerts a direct influence on the contractile ability of the muscle[18,19]. Additionally, increases in running speed lead to higher impact forces being imposed on the lower limbs[20] and greater levels of neuromuscular engagement (mainly in the hamstring muscles)[21]. The concomitant increase in muscle acidity and decrease in phosphagen stores with muscle fatigue alters muscle force generation capabilities[22], which may be linked to changes in joint movement patterns[23–27] and running mechanics[28] often linked to running injury[28,29]. Due to a lack of studies evaluating injury occurrence, the effects of more strenuous runs on these markers are still unknown. Having taken risks and benefits into consideration, coaches must themselves decide how to manage HIIT inclusion in running plans for endurance athletes, for example, how many sessions per week and the duration of work and relief periods or intensities. Knowledge about either the acute changes induced by HIIT protocols or the long-term adaptations induced by HIIT-based interventions in endurance runners plays a key role in the training prescription process.

To the best knowledge of the authors, fourteen reviews have so far been performed about HIIT[5–9,30–38], of which only two[32,35] were systematically performed and included information about literature search strategies. Five of these fourteen works focused on sprint interval trainings (SIT), with work periods at maximal intensities[30–32,35,36], whereas the other nine considered different HIIT regimes at submaximal intensities. As for the type of population, three works focused on active healthy people[32,35,37], whilst the other eleven related to trained athletes. Among them, only Billat et al. focused on endurance runners, with two works published in 2001 [6,7]. Therefore, a systematic review that summarises findings and new evidence about how HIIT affects non-elite endurance runners in the short- and long-term is needed and is the main purpose of the current work.

2. METHODS

2.1 Search Strategy

Electronic databases, including Pub Med, Science Direct, Web of Science and Sports Discuss were searched for literature dating from January 2000–October 2015. Keywords used were ‘‘high-intensity intermittent training’’ OR ‘‘high-intensity interval exercise’’ OR ‘‘interval running’’ OR ‘‘sprint interval training’’ AND ‘‘endurance runners’’ OR ‘‘long distance runners’’. The search was limited based on text availability (full text available), publication date (from January 2000–October 2015), species (humans), language (English) and age (≥18 years). Duplicates between searches were removed. Results of the search procedures are summarised in Figure 1.

FIGURE 1 ABOUT HERE

2.2 Selection Criteria

Studies were included in the review if they met the following criteria: (a) published in peer-reviewed journals; (b) including participants 18 years or older; (c) involving non-elite endurance runners; (d) using run-based testing sessions and in the case of intervention studies, run-based training programmes. Studies were excluded if they: (a) did not meet the minimum requirements of an experimental study design (e.g. case reports); (b) did not meet the minimum requirements regarding training design (e.g. lack of information on volume, frequency, and/or intensity of training); (c) were not written in English; (d) involved untrained subjects, team sport athletes, or non-endurance runners. Additionally, reviews were not included in this systematic review. Based on the inclusion and exclusion criteria, two independent reviewers (FGP, PALR) screened citations of potentially relevant publications. If the citation showed any potential relevance, it was screened at the abstract level. When abstracts indicated potential inclusion, full text articles were reviewed. A third-party consensus meeting was held with VMSH if the two reviewers (FGP, PALR) were not able to reach agreement upon inclusion of an article.

2.3 Quality Assessment

Given that there is no consensus regarding reliable and valid instruments for the assessment of the methodological quality of cross-sectional studies[39], neither rating nor weighting of studies was conducted. However, different aspects of methodological quality (e.g. participant characteristics, exercise protocol, tests performed and major findings) were extracted from the articles and are reported in the results section.

For intervention studies, two independent reviewers (FGP, PALR) performed quality assessments of the included studies and disagreements were resolved through a consensus meeting or a rating by a third assessor (VMSH). Initially, methodological quality was assessed using the Physiotherapy Evidence Database (PEDro) scale[40], an 11-item scale that rates randomised controlled trials from 0–10, with 6 representing the cut-off score for high-quality studies. One question was used to establish external validity and was not included in the score. Only studies with PEDro scores of 6 or higher were considered for the systematic review[40]. Maher et al.[40] demonstrated fair-to-good inter-rater reliability with an intra-class correlation coefficient of 0.68 when using consensus ratings generated by two or three raters. Eight studies met the inclusion criteria[10–17]. Consensus was achieved on scores given to the nine articles.

2.4 Data Extraction

Data were extracted using a standardised form created in Visual Basic to filter the required information into a continuous string in Microsoft Excel. The form included a hierarchy for assessment including the study citation and the inclusion/exclusion criteria. Studies were assessed first by journal title, second by abstract, and third by full article review. At this point the journal article was either included or excluded based on the criteria illustrated in Figure 1.

3. RESULTS

The results for cross-sectional and longitudinal studies are presented separately. Table 1 (cross-sectional studies, n=15) and Table 2 (intervention studies, n=8) summarise the essential parameters of the selected studies.

TABLE 1 ABOUT HERE

TABLE 2 ABOUT HERE

3.1. Cross-sectional studies

In the fifteen cross-sectional studies selected, non-elite endurance runners performed at least one HIIT protocol and the acute impact on physiological, neuromuscular, metabolic and/or biomechanical variables was assessed.

Most studies used heart rate (HR) and blood lactate accumulation (BLa) to control the exhaustion level reached and to monitor the physiological and metabolic response to HIITs, whereas some of them included hormone response[41], energy expenditure[42], lipids response[42], gas exchange analysis (VO_2, CO_2 production, respiratory exchange ratio, post-exercise oxygen consumption)[26,42–51] and running economy (RE)[26]. Biomechanical variables were controlled in some of the aforementioned works with spatial-temporal parameters[45] and running kinematic from a sagittal plane[26], while the impact of HIIT protocols at a neuromuscular level was assessed in four studies[45,52–54].

Some studies focused on describing the response to a specific HIIT running protocol[41,52,54], while others made a comparison between the responses to HIIT and a continuous run (CR),[42,48,51] or between different HIIT running protocols[26,43–47,49,50,53]. In the study by García-Pinillos et al.[53], participants performed typical running workouts, varying in intensity (in terms of average running pace), duration of work and relief intervals, but with similar density and total distance (4km). Similarly, Kaikkonen et al.[44] utilised running protocols with the same volume (3km), but different intensity (85–105% velocity associated to VO_{2max} [VVO_{2max}]) and different durations of work and rest periods. On the other hand, Seiler and Hetlelid[43] and Collins et al.[26] focused on the manipulation of resting time but maintained work intervals, with workouts performed at a self-selected pace, whilst Millet et al.[46], Wallner et al.[47] and Billat et al.[49] maintained constant work and rest intervals but modified the intensity (30s-30s during T_{lim}, 10s-20s during 30min, and 15s-15s up to exhaustion, respectively). Finally, Vuorimaa et al.[45] and Seiler et al.[50] compared HIIT protocols with identical volume and work–rest ratios, but differing work and rest intervals (at a VVO_{2max} and self-selected pace, respectively).

3.2. Intervention studies

PEDro scores for the eight selected articles ranged from 6 to 7 out of a maximum of 11 (Table 3). One article[55] was excluded because of the score obtained. Concealment of allocation is not entirely relevant in studies of this nature, because given the nature of endurance training and the sample selection methods used it is difficult for researchers to keep themselves and participants unaware of the treatment and groups involved. Blinding of subjects and therapists (i.e. trainers) was also not applicable in this case.

TABLE 3 ABOUT HERE

From the eight articles included in Table 2, seven used a high-volume low-–moderate-intensity continuous training (CT) programme for the control group[10–14,16,17]. Likewise, three studies included two HIIT-based intervention groups[14,15,17], with one of them[15] not including a control group. All of these studies lasted a minimum of four weeks, with ten weeks being the longest intervention period[14] and including up to two[14,1513,17], three[11,12,16] or four [10] HIIT sessions per week. Most of these studies combined HIIT sessions with CR sessions for intervention groups, with only two works exclusively performing HIIT[12,16] (in both studies this included three sessions per week). In order to check the effectiveness of the training programmes, all these studies included gas exchange analysis during an incremental running test. Likewise, HR and BLa were used to control possible changes in the acute response to running protocols. Moreover, among the outcome measures, one study included some indexes of oxidative stress[16], while others included muscle proteins and enzymes[10] or parameters related to muscle morphology[13]. Blood analysis, further than BLa, was performed in four of these studies[10–13], while all studies assessed the athletic performance of participants.

4. DISCUSSION

The purpose of this systematic review was to critically analyse the literature to determine how HIIT affects non-elite endurance runners in the short- and long-term. The main findings from the cross-sectional studies included in this review are: (a) at a neuromuscular level, trained endurance runners are able to maintain an adequate muscular performance after a HIIT workout, whilst high-intensity CR impairs muscular performance; (b) at a physiological level, the main difference between CR and HIIT is the energetic metabolic pathway that is activated; there is a greater activation of anaerobic lactic metabolism during HIIT; (c) at a biomechanical level, HIIT sessions including runs for 1–2min and performed at intensity close to VO_{2max} do not consistently perturb the running kinematics of trained male runners. On the other hand, the major outcomes from intervention studies included in this review are: (a) HIIT-based training programmes are effective in improving athletic performance in non-elite endurance runners; (b) exercise bouts at an intensity close to or above the intensity corresponding to VO_{2max} appear to be more effective in improving performance and VO_{2max} compared with moderate-intensity exercise training; (c) HIIT-based running plans appear to be effective in improving RE in trained endurance runners; (d) HIIT causes an increased oxidative capacity of a greater number of muscle fibers and a reduced plasma K^+ concentration which contributes to the maintenance of muscle function during intense exercise and delays the apparition of fatigue. However, caution should be exercised when interpreting these findings, due to the heterogeneity that exists among study protocols. In the next section, acute responses to HIIT (including cross-sectional studies) and long-term adaptations to HIIT interventions (including HIIT-based training programmes) are discussed separately.

4.1. Acute responses to HIIT-based running protocols

Many variables, at least nine, can be manipulated to prescribe different HIIT sessions and among them, the intensity and duration of work and relief intervals are the key influencing factors[8,9,34]. Then, the number of intervals and the number of series and between-series recovery durations and intensities determine the total work performed. From the analysis of cross-sectional studies included in this review, the authors state that the manipulation of each variable in isolation likely has a direct impact on metabolic, cardiopulmonary and/or neuromuscular responses. When more than one variable is manipulated simultaneously, responses are more difficult to predict, since the factors are inter-related, making it unclear which combination of work-interval duration and intensity, if any, is most effective at allowing an individual to spend prolonged time at VVO_{2max} while ‘controlling’ for the level of anaerobic engagement[6] and/or neuromuscular load[7].

4.1.1. Acute neuromuscular changes after HIIT-based running exercises

The available evidence about neuromuscular engagement after a run-based HIIT is limited. In the current review, four of the revised manuscripts[45,52–54] examined the neuromuscular response to a HIIT workout in non-elite endurance runners, and all of them did this through indirect measures related to muscular performance (i.e. jumping, balancing and grip strength testing). While Latorre et al.[52] and García-Pinillos et al.[54] examined the impact induced by a single HIIT protocol, García-Pinillos et al.[53] and Vuorimaa et al.[45] compared the changes induced by different HIIT workouts, but none of these studies made a comparison with a CR protocol. Despite differences in the running protocols, all were performed at a velocity close to VVO_{2max}, accumulated longer work periods than 10min at the aforementioned velocity, and consequently, led to high levels of exhaustion in terms of BLa, rate of perceived exertion (RPE) and mean and peak heart rate.

In general, all of these studies agree on the lack of impairment in muscular performance parameters for trained endurance runners performing a HIIT workout. Some of these studies[52–54] even discussed the presence of the post-activation potentiation phenomenon, whereby there is a significant vertical jump performance improvement after running. It is known that endurance training causes, on one hand, a greater amount of phosphorylation of regulatory myosin light chains in slow fibers, and on the other hand, a greater resistance to fatigue, which allows for the prevalence of potentiation and may explain the post-activation potentiation presence in endurance athletes[56]. Therefore, the ability to sustain adequate muscular performance and to tolerate fatigue during HIIT seems to be typical for endurance runners.

Nevertheless, none of these studies include a comparison with CR, so the effects of CR at a neuromuscular level remain unknown. Contradictory results can be found in recent literature; while some previous works have reported 8–16% reductions in jumping test performance (drop jump and repeated jump tests) after a marathon[57] and a negative influence of intensive aerobic running (6km at velocity related to lactate threshold) on some muscle contractile characteristics (i.e. an impaired excitation-contraction coupling), a previous work by Vuorimaa et al.[58] investigated acute changes in muscle activation and muscular power performance after 40min of CR at an intensity of 80% VVO_{2max} in elite long-distance runners and showed an enhanced jumping performance post-exercise. These data suggest that trained endurance runners are able to maintain an adequate muscular performance after low- or moderate-intensity CR but greater distances (i.e. marathon or half-marathon) or greater intensities (similar to that maintained during HIIT) might impair muscular performance.

4.1.2. Acute effect of HIIT-based running protocols on physiological parameters

Compared with CR, there is no doubt that differences in the impact of HIIT-based runs exist at a physiological level [41,42,48,51]. A different hormone response, in terms of salivary cortisol and testosterone concentrations post-exercise, was found after CR (30min at lactate threshold intensity) and HIIT (6 x 3.5min at 90% VO_{2max}), with increased concentrations after HIIT compared with CR[41]. O´Brien et al.[51] found that despite total work durations of CR and HIIT protocols being similar (~20min), HIITs, with intervals of 100–50% VVO_{2max}, resulted in greater mean average VO_2 than CR, with CR runners spending 1–7min above 90% VO_{2max} and no participant exceeding 90% VO_{2max}. Similar results were found during runs up to exhaustion[48] (both CR and HIIT, with work periods performed ~90–95% VVO_{2max}), with higher VO_{2max} values reached during HIIT and longer times above 90% $VO_{2max,}$ so that HIIT was more effective than CR in stimulating aerobic metabolism, with a longer time to exhaustion, a longer time at VVO_{2max} and higher VO_{2max} with lower BLa. Besides supporting these findings, Hernandez-Torres et al.[42] added that energy expenditure was higher during HIIT (based on higher VO_2 values), and reported different effects on the lipids response; both HIIT and CR increased total cholesterol (TC), where high-density cholesterol (HDL-C) increased with HIIT and low-density cholesterol (LDL-C) increased with CR. Taken together, the intermittent profile of HIIT workouts allows a high stimulation of aerobic metabolism (even greater than in CR) as well as a greater activation of anaerobic lactic metabolism. Thus, the main difference between CR and HIIT is the energetic metabolic pathway that is activated.

Different physiological responses to CR and HIIT might be expected, but what between about different HIIT protocols? Whereas some studies found differences in the physiological response to the compared protocols[43–45,47,49–51], others did not[26,53]. Differences in protocols make comparisons difficult. It seems clear that during short HIIT-based protocols with fixed durations of work and relief intervals (30s-30s[46]; 15s-15s[49]; 10s-20s[47]), an increased intensity, in terms of running pace, elicits greater VO_{2max}, BLa, HRpeak and RPE and a longer time above 90% $VV0_{2max}$. But what happens during longer intervals? Some studies have compared the response to different HIIT protocols. By using short HIITs (100m runs at ~130% VVO_{2max}), a study by García-Pinillos et al.[53] reported a similar physiological impact, in terms of BLa and HR response, to that of a longer HIIT (based on 400m runs at ~105% VVO_{2max}). However, doubling the duration of work and relief intervals (from 1–2min) but maintaining running intensity (at VVO_{2max}) and the work–rest ratio (1:1), the physiological demands changed significantly with increased aerobic energy release, BLa and VO_{2max}[45,51]. In a similar study, but performed at self-selected pace, Seiler et al.[50] concluded that a higher number of shorter runs increases VO_{2max} during recovery and decreases it during exercise, but with intervals lasting 2–6 min protocols showed a similar VO_2 kinetic. Additionally, duration and intensity of relief intervals during HIIT workouts are influencing factors. In Seiler and Hetlelid´s study[43], longer work bouts (lasting 4 min) were undertaken and changes in recovery periods (1, 2 or 4min) induced a 2% increase in average work intensity with no differences in $V0_2$. Likewise, RE impairment with changes in substrate utilisation – an increased dependency on fat oxidation – has been reported after HIIT (based on 400m runs) and independent of recovery time (1, 2 or 30 min[26]). Taken together, HIIT protocols involving short work periods (~20–30s), work–rest ratios close to 1:1 and performed close to maximum intensities (with indications such as ‘complete the protocol as fast as you can’) enable athletes, compared to longer HIIT or CR protocols, to train at an increased running pace (widely above VVO_{2max}) and to elicit similar, or even greater, mean average VO_2.

4.1.3. Acute fatigue-induced changes in biomechanics of running during HIIT

The effect of exertion on running kinematics has been extensively studied[23–26,28,59–62]. However, most of these studies were performed in laboratory conditions and with athletes performing prolonged treadmill runs[23,24,27] or running-induced fatigue protocol on treadmills[22,25,59]. The generalisation of results from studies that analyse running on a treadmill may become controversial if treadmill and overground running biomechanics are not proven to be equivalent[63,64].

The evidence about changes induced by HIIT running protocols is quite limited. From all the studies included in this review, only two works[26,45] assessed the HIIT-induced changes to the biomechanics of running. Both agreed that HIIT sessions including runs for 1–2min and performed at intensity close to VO_{2max}, did not consistently perturb the running kinematics of trained male runners.

In turn, after CR protocols, some studies found fatigue-induced changes during running at kinematic level, for example,, increased hip extension[62], decreased knee flexion angle at foot strike[24], increased step length with a corresponding decrease in cadence[23] and changes in foot strike pattern[60,61]. Thus, based on the biomechanical response to CR and HIIT protocols, and being especially cautious because of the wide variety of running protocols used, the authors suggest that CR causes greater impairments to running kinematics than HIIT protocols, including runs for 1–2min and performed at intensity close to VO_{2max}.

Cross-sectional studies have limitations because the outcomes from correlative analyses do not allow the identification of a cause-and-effect relationship. Accordingly, intervention studies have to be conducted to detect cause-and-effect relationships. The subsequent section will discuss intervention studies that examined the effects of HIIT-based running programmes on parameters related to endurance performance (neuromuscular, physiological and biomechanical parameters).

4.2. Long-term adaptations to HIIT-based running programmes

Besides the elevated number of variables that can influence the acute effect of every single HIIT session (see above), determining the effectiveness of an intervention requires parameters such as duration (weeks or months), frequency (sessions per week), methodology (type of workouts) and periodisation (progress of the training load) to be taken into consideration. Additionally, when coaches prescribe training programmes, they essentially pursue two objectives: (1) to improve athletic performance and (2) to avoid injuries. The following sections will cover these elements.

4.2.1. Changes in athletic performance after HIIT interventions

Despite differences in training programmes conducted by these studies[10–17], all agree that athletic performance improved after HIIT intervention. Esfarjani et al.[14] underwent the longest intervention included in this review (10 weeks), by combining CR with HIIT (at 100% VVO_{2max}, G_1) or SIT (30s runs at 130% VVO_{2max}, G_2) in four sessions per week; performance in a 3km time trial increased by 7.3% and 3.4% (G_1 and G_2, respectively). After nine weeks combining low–moderate-intensity CR with HIIT and SIT sessions in a total of six sessions per week, Bangsbo et al.[10] found performance in 3km and 10km time trials increased (3.3% and 3.1%, respectively). Even during shorter interventions[15,17] the combination of habitual CR sessions and two HIIT sessions per week over four weeks have seen improvements in 1.5km (2%), 3km (1.1–2.7%), and 5km time trials (1.5–2.3%). All these studies implemented traditional endurance training sessions with HIIT-based workouts, but other authors went further and prescribed running plans exclusively using HIITs. Gunnarsson et al.[12] replaced the regular endurance training programme (high-volume and low-intensity) with a HIIT-based intervention (10-20-30 training concept) three times per week, and reported 6% and 4% improvements in 1.5km and 5km time trials respectively, after seven weeks of intervention. Based on these results, the presence of at least two sessions of HIIT workouts in a running plan allows trained endurance runners to improve their athletic performance. But what about the duration of work intervals during HIIT? Some of these studies included SIT (all-out efforts lasting 20–30s with long resting periods of 3–5min)[10,14], others aerobic HIIT with long work intervals (2–4min at intensity of ≤100% VVO_{2max})[10,14,15,17], and others[11–13,16] HIIT with short work intervals (lasting 20–60s) at intensities >VVO_{2max}. Based on these findings, the authors suggest that HIIT and SIT must be a part of running plans for endurance athletes, but training periodisation should take the progressive overload principle into consideration. For example, during a traditional periodisation (increasing intensities and decreasing volumes) HIIT should move from long runs to shorter and faster runs, whilst SIT should be progressively included from short sprints to 25–30s all-out efforts.

On the other hand, despite the suggested association between increased running speed and running injury[28,29], none of these studies have directly measured or monitored injury risk factors during HIIT intervention. Only Smith et al.[17] monitored subjective ratings of sleep, fatigue, stress and muscle soreness, with no changes reported during the four week intervention. Therefore, it seems that consensus exists about the benefits of HIIT interventions for endurance performance even though more longitudinal studies covering the effects of HIIT-based training programmes on injury risk-factors for endurance runners are needed. Moreover, why does endurance performance improve when running intensities during workouts are increased? In order to answer this question, long-term neuromuscular and physiological adaptations to HIIT interventions are examined below.

4.2.2. Changes in gas exchange measurements after HIIT-based running plans

It is well known that VO_{2max} is one of the main factors behind performance in endurance events[65]. Likewise, it is documented that exercise bouts at an intensity close to or above the intensity corresponding to VO_{2max} appear to be more effective in improving performance and VO_{2max} than moderate-intensity exercise training[5–9,30–38]. Most of the studies examined in this review reported greater VO_{2max} improvements after HIIT interventions than after traditional training plans[11–14,16]. However, some of them did not find significant changes in VO_{2max}[10,17]. This might be because both studies involved experienced runners with already high VO_{2max} values (>60ml/kg/min), thereby making improvement difficult. Moreover, both studies reported improvements in athletic performance and VVO_{2max} after the intervention period. Hence, that finding supports the extended statement that while VO_{2max} is an influencing factor in endurance performance it is not the only one, with other physiological and neuromuscular parameters (i.e. metabolic thresholds, anaerobic capacity, and efficiency[65]) playing key roles.

Related to VO_{2max} is the concept of RE, the energetic cost of running at a given speed[66]. Most of these studies[10,13,15,17] considered RE as a influencing factor in endurance performance and hypothesised that including repeated bouts of faster runs (HIIT) in their running plans, would lead to improvements in RE for endurance-trained runners. However, the results reported by these studies are equivocal. Whereas Gliemann et al.[13] found no change in RE after eight weeks of combining HIIT (10-20-30 training concept, two sessions per week) and CR (one session per week), other studies reported RE improvements after four[15,17] and nine[10] weeks of training programmes that included HIIT sessions. Looking at the training programmes performed in those studies, the equivocal results obtained may depend on two factors: the weekly running distance or the intensity of the HIIT. As suggested by Denadai et al.[15], improvements in RE with HIIT may result from improved muscle oxidative capacity and associated changes in motor unit recruitment patterns. Ensuring a minimum weekly mileage is important in improving muscle oxidative capacity and Gliemann et al.[13] reduced it to ~15-km per week, while the studies reporting RE improvement reached greater weekly mileage. As for the intensity of the HIIT, the importance of neuromuscular characteristics (motor unit recruitment and contractile properties) in determining RE and performance has recently been pointed out by Nummela et al.[67]. Whilst, Gliemann et al.[13] based their running plan on a 10-20-30 training concept performed, on average, at 85% HRmax and under 100% VVO_{2max}[12], the HIIT workouts included in the studies reporting RE improvements were performed at VVO_{2max} or above. The findings of Denadai et al.[15] support this rationale with RE improving after the training programme including HIIT at 100% VV_{O2max} but not after HIIT at 95%. These data suggest that in order to improve RE in trained endurance runners, coaches should pay special attention to weekly mileage (combining HIIT and CR may be a good way to ensure a minimum mileage) and intensity of HIITs (close to or above 100% VVO_{2max}).

4.2.3. Muscular adaptations to HIIT-based running plans

Improved global oxygen consumption/delivery also corresponds with changes in muscle fiber, in which type I fibers have greater oxidative capacity than IIa and IIx fibers. Interval training, by affecting glycolytic capacity, may also lead to increased mitochondrial activity in type II fibers and thus show characteristics similar to those of type I fibers[65]. Training at maximal and near-maximal exercise intensities also seems to be effective in creating muscular adaptations such as increases in the activity of oxidative enzymes and expression of Na+-K+ pump subunits and lactate and H+ transporters[10,12,13,16]. Moreover, HIIT causes repeated VO_2 fluctuations related to changes of exercise intensity, as opposed to CR where VO_2 is nearly constant during the exercise. Due to this, a higher exercise-induced oxidative stress could be expected, however HIIT- and CR-based training programmes induced similar beneficial effects in endurance runners, reducing the resting levels of oxidative stress biomarkers in plasma and urine[16]. Therefore, since all these studies reported athletic performance improvements after a HIIT intervention longer than seven weeks but did not all find VO_{2max} or RE improvements, muscular adaptations to a HIIT period may play a critical role in the performance improvement of endurance runners.

On the other hand, no changes in muscle morphology occurred after seven to eight weeks of run-based endurance training[12,13], either in CR- or HIIT-based training programmes. Likewise, capillary to fiber ratio and capillary density were unaltered after seven to eight weeks of HIIT-based running protocols (10-20-30 training concept)[12,13]. These data suggest that HIIT running protocols are less effective in improving capillarisation than prolonged running, and suggest that 10-20-30 training evokes weaker angiogenic stimuli than moderate-intensity exercise training. Since muscle capillarisation is important for the delivery of oxygen and nutrients to the exercising muscle (a higher capillary density can increase muscle to blood exchange surface, decrease oxygen diffusion distance and increase red blood cell mean transit time) these findings lead to the authors supporting the idea that both HIIT and CR must be part of training programmes for endurance runners in order to maximise the physiological adaptations to training.

4.2.4. Changes induced in blood variables – at rest and after exhausting runs -

Most of the intervention studies included in this review collected BLa at the end of an exhaustive running protocol[10–12,17]. Some of these studies reported no adaptations after HIIT intervention[11,12], whilst other works[10,17] found significant changes, so it seems that improved short-term performance can occur without changes in some of the key H^+ transport proteins. Bangsbo et al.[10] found changes in BLa clearance (but not in peak BLa) in athletes who had completed the HIIT intervention, whereas the CR group remained unchanged. Since maximal muscle oxidative capacity is related to BLa removal ability, the authors suggest that the differences in BLa clearance might be due to an oxidative capacity improvement during the HIIT period. From this thinking, either the lack of changes in BLa together with the performance improvement (similar BLa despite a greater athletic performance) reported by some studies[11,12], or the reduction of BLa after a running protocol performed at the same relative intensity[17], are indications of improved buffer capacity and H^+ clearance in working muscle. Hence, training at high intensity can delay the accumulation of lactate in the blood, which may be due to an increased oxidative capacity of a greater number of muscle fibers and/or a reduced plasma K^+ concentration (plasma K^+ contributes to the maintenance of muscle function during intense exercise[10]). The training protocols used by these studies are different, with a 10-20-30 training session performed two[13] or three[12] times per week, HIIT with longer intervals at VVO_{2max}[17] and a training programme where CR, HIIT and SIT are combined[10], so although results must be interpreted with caution, increased intensity in a running plan seems to be effective in improving oxidative capacity when compared to a CR-based plan.

Regarding resting blood variables, two studies[12,13] examined changes in blood haemoglobin and plasma iron, glucose, myoglobin, creatine kinase, cortisol, insulin, and triglycerides induced by intervention training programmes. Although intense aerobic training is generally associated with improved blood lipid profile and insulin sensitivity, the results reported by these studies are equivocal, probably because the athletes were already trained at the beginning of the intervention.

5. Conclusions

Since HIIT running sessions lead, in the short-term, to increased cortisol and testosterone concentrations, greater mean VO_2, longer times above 90% VO_{2max}, higher energy expenditure and different effects on lipids response, and there being no reported `extra´ neuromuscular strain or consistent perturbations in running kinematics (when compared to moderate-intensity CR), they are an efficient option for endurance runners in response to demands of higher average intensities and lower weekly running distances (for injury prevention and performance improvements, respectively). Because of this, some studies have checked the effectiveness of HIIT-based running plans (minimum of four week programme, at least two HIIT sessions per week and mostly combining HIIT and CR workouts) and shown athletic performance improvements in trained endurance runners by improving VO_{2max} and RE along with muscular and metabolic adaptations (increased oxidative capacity of a greater number of muscle fibers and reduced plasma K^+ concentration).

From a practical point of view, the authors support the idea that both HIIT and CR must be part of training programmes for endurance runners in order to maximise adaptations to training. Additionally, the authors suggest that the inclusion of two to three HIIT sessions in a running plan, accumulating longer work periods than 10min and working at close to or above VVO_{2max} per session lets non-elite endurance runners improve their athletic performance. But, what type of HIIT? In general, HIIT protocols involving short work periods (~20–30s) with work–rest ratios close to 1:1, and performed close to all-out intensities enable athletes to elicit similar or greater mean average VO_2 and to train at an increased running pace (above 100% VVO_{2max}) when compared to longer HIIT or CR protocols would be a good tool for endurance runners. Nevertheless, the authors highlight that although HIIT and SIT, together with CR, must be a part of running plans for endurance athletes, the HIIT-based workload will vary according to training periodisation, which must be based on the progressive overload principle.

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Table 1. Studies (n= 15) examining the acute effects of HIITs on physiological, metabolic, neuromuscular and biomechanics measurements in recreationally trained endurance runners.

Study	Subject description	Study design	Exercise protocol	Outcome measures	Results
Latorre et al.[52]	*n* = 16 males 29.6 ± 7 years BMI 23±2 kg/m^2 VO_{2max} 56±3 ml/kg/min *Non-elite *≥6 yr experience	Unilateral cross-over. All participants performed the running protocol *A field-based study (on a track)	4 x 3 x 400 m: 12 runs of 400 meters, grouped into 4 sets of 3 runs, with 1-min passive recovery between runs, and 3-min between sets	*Physiological response:* - BLa and HR *Neuromuscular response:* - CMJ and HS *Athletic performance:* - Running pace	- CMJ and HS performances are = despite high level of exhaustion - CMJ performance (resting vs. 1st set): Post-activation potentiation
Tanner et al.[41]	*n* = 10 males 39.3 ± 6 years 76.6 ± 8 kg VO_{2max} 59±6 ml/kg/min *Recreational * 4-8 ss/wk	Repeated measures. All participants completed 5 trials in randomised order. *Laboratory conditions.	i) HIIT: 6 runs of 3.5 min at 90% VO_{2max}, with2 min of recovery at 30% VO_{2max} ii) CR: 30 min at LT iii) a bodyweight-only circuit session	*Physiological response:* - HR, hormone response (cortisol and testosterone) *Athletic performance:* - Running speed - %VO_{2max}	- ↑ cortisol concentration after the HITT, compared to others. - ↑ testosterone post-exercise in both running based exercise trials (over 50% higher than pre-)
García-Pinillos et al.[53]	*n*= 18 (16 M, 2 F) 30.9 ± 11 years BMI 22±2 kg/m^2 VVO_{2max} 17±1 km/h *Recreationally-trained *4-6 ss/wk	Repeated measures. All participants completed 2 trials in randomised order: *A field-based study (on a track)	i) HIIT: 10 × 400 m, 90 s recovery between runs ii) HIIT: 40×100 m, 30 s recovery between runs *A passive recovery between runs *Both protocols were carried out >VVO_{2max}	*Physiological response:* - BLa, HR *Neuromuscular response:* - Postural control, jumping test, stretch-shortening cycle (SSC) *Athletic performance:* - Running pace	- Despite = training volume (4 km), 40×100 m enabled runners to train at a higher pace (+3.13 km/h) - 40×100m = vertical jump ability, postural control or SSC - 10×400m: ↓ postural control and caused ↑ vertical jumping tests. - = HR and BLa response
Hernandez-Torres et al.[42]	*n* = 15 males 22.8 ± 5 years BMI 20±2 kg/m^2 VO_{2max} 77±3 ml/kg/min *5-6 ss/wk) *>1 year training	Repeated measures. All participants completed 2 trials in randomised order: CR vs. HIIT *Laboratory conditions	Two single exercise sessions of = duration (90 min) and = distance (14 km): i) CR: ~ 45% VO_{2max} ii) HIIT: 22 reps of ~40% VO_{2max} for 3 min, and ~ 75% VO_{2max} for 1 min	*Physiological response:* - VO_2 and CO_2 - BLa and HR - Blood lipids *Metabolic response:* - EE and RER	- HIIT ↑ higher level of intensity than CR (%HR_{max}: +13.8%; %VO_{2max}: +14.83%; RER: 5.83%), and ↑ EE - Different effects on the lipids response: HIIT ↑blood TC and HDL-C; CR ↑blood TC and LDL-C - Main difference CR vs. HIIT: energetic metabolic pathway activate

Seiler and Hetlelid [43]	*n* = 9 males 30.0 ± 4 years 72 ± 5 kg 181±6 cm VO_{2max} 72±5 ml/kg/min *Trained athletes	Repeated measures. All participants completed 3 treadmill HIIT in randomised order. *Laboratory conditions	6 x 4-min work bouts with either 1-, 2-, or 4-min recovery periods were performed in each session. *Self-paced: the highest possible average running speed for the work intervals	*Physiological response:* - BLa and HR - Gas exchange *Athletic performance:* - Running velocity	- Running velocity: ↑recovery time (1 to 2 min) resulted in a ↑2% average pace; resting 4 min = work intensity - VO_2: 3-6 min bouts are performed at 90–100% VO_{2max}. No differences between protocols were found - BLa: 4 mmol/L after 1st run and 6–7 mmol/L at the end
Kaikkonen et al. [44]	*n* = 13 males 35 ± 5 years 76.6 ± 5.6 kg VO_{2max} 54±3 ml/kg/min *Recreational *4-5 ss/wk	Repeated measures. All participants completed 3 treadmill HIIT in randomised order. *Laboratory conditions	3 HIITs for = distance (3 km): i) $HIIT_1$:2x6x250 m/rec 30 s/5 min at 85%V_{max} ii) $HIIT_2$:, 2x3x500 m/rec 1 min/ 5 min at 85% V_{max} iii) $HIIT_3$:, 2x6x250 m/rec 30 s/5 min at 105% V_{max}	*Physiological response:* - VO_2, CO_2 and EPOC - BLa, HR and HRV *Athletic performance:* - Running velocity	- $HIIT_3$ caused ↑HR, EPOC, VO_{2max} and BLa
García-Pinillos et al. [54]	*n* = 30 males 38.2 ± 8 years BMI 22±3 kg/m^2 VO_{2max} 58±4 ml/kg/min *Recreational *5-8 ss/wk	Unilateral cross-over. All participants performed the HIIT *A field-based study (on a track)	4 x 3 x 400 m: 12 runs of 400 meters, grouped into 4 sets of 3 runs, with 1-min passive recovery between runs, and 3-min between sets	*Physiological response:* - BLa, HR *Neuromuscular response:* - CMJ and HS *Athletic performance:* - Running pace	- High exhaustion level (RPE: 18.4; HRpeak: 182.2; HRrec: 155.4; and BLa: 13.6) - Despite that, trained subjects = strength and power levels and work capacity
Collins et al. [26]	*n* = 7 males 25.4 ± 4 years 68.8 ± 7 kg 180 ± 7 cm VO_{2max} 72±3 ml/kg/min *>1 yr of training *>40 km per week	Repeated measures. All participants completed 3 treadmill HIIT in randomised order. *Laboratory conditions	3 HIIT sessions with running economy tests at 3.33 and 4.47 m/s: i) 10x400 m, 1 min rec ii) 10x400 m, 2 min rec iii) 10x400 m , 3 min rec *Protocols were carried out at VVO_{2max}	*Physiological response:* - VO2, RER - RE (based on VO2). *Kinematic data:* - 2D analysis *Athletic performance:* - Running pace	- After HIIT sessions at 100%VO_{2max} the VO_2↑ independent of the recovery condition. - ↓ RE after HIITS - Irrespective of the duration of recovery, running kinematics =
Vuorimaa et al. [45]	*n* = 10 males 22 ± 3 years 66.7 ± 7 kg 178 ± 5 cm VO_{2max} 72±3 ml/kg/min *Trained runners *National level	Repeated measures. All participants completed 2 treadmill HIIT in randomised order. *Laboratory conditions	i) $HIIT_1$: 14 x 60 s runs with 60 s rest at VVO_{2max} ii) $HIIT_2$: 7 x 120 s runs with 120 s rest at VVO_{2max}	*Physiological parameters* - VO_2, VO_{2max}, AOD - HR, BLa *Muscular performance* - CMJ - Stride length	- Runners = CMJ and stride length - Both protocols showed high aerobic energy releases (70% and 80%, resp). - Small AOD during both HIIT - PeakVO_2, relative aerobic energy release and BLa ↑ when the duration of running bouts was doubled.

Millet et al. [46]	*n* = 7 males 21 ± 3 years 64.7 ± 6 kg VO_{2max} 72±3 ml/kg/min *Endurance athletes *40-60 km/week	Repeated measures. All participants completed 2 HIIT in randomised order.	2 HIIT sessions consisting: 3 x *n* intervals [*n* x 30 s = T_{lim}] i) $HIIT_{100\%}$: 30s work intervals at 100% VVO_{2max} with 30s recovery at 50%VVO_{2max} ii) $HIIT_{105\%}$: Identical, but work intervals at 105%VVO_{2max}	*Physiological parameters* - VO_2, VO_{2max} and HR *Performance variables:* - Time (s) ≥90% VVO_{2max} - Time (s) ≥90% HR_{max}	- $VO2_{peak}$ and running pace ↓ $HIIT_{100\%}$ than in $HIIT_{105\%}$ - HR_{peak} and RPE ↓ in $HIIT_{100\%}$ than in $HIIT_{105\%}$ - Time >90%VO_{2max} ↑ $HIIT_{105\%}$ than in $HIIT_{100\%}$. Time spent >90%HR_{max} ↑ $HIIT_{105\%}$ than in $HIIT_{100\%}$
Wallner et al. [47]	*n* = 8 males 24.5 ± 3 years BMI 22±1 kg/m^2 VO_{2max} 55±3 ml/kg/min *Trained male runners	Repeated measures. All participants completed 3 HIIT in randomised order. *Laboratory conditions	3 HIITs were performed at VVO_{2max} (10s work, 20s passive recovery, during 30 min): i) at 50% at VLTP ii) at 55% VLTP iii) at 60% VLTP	*Physiological parameters* - VO_2 and VO_{2max} - HR, BLa *Performance variables:* - VLTP	- Short HIITs with passive rest phases gave an overall aerobic metabolic profile similar to CR - Mean $V0_2$↑ in ascending order of intensity. - BLa = level at the end of warm-up
Demarie et al. [48]	*n* = 15 (3F, 12 M) ~ 45 ± 7 years F: 51 ± 3 kg M: 72 ± 6 kg *Sub-elite *VO_{2max} 56±4 ml/kg/min	Repeated measures. All participants completed 3 sessions. *A field-based study (on a track)	i) CR: up to exhaustion at 90-95% VVO_{2max}. ii) HIIT with a 2:1 work:rest ratio. Exercise periods at 90-95% VVO_{2max} during ½ T_{lim}, whereas recovery periods at 50% VVO_{2max}. during ½ T_{lim}.	*Physiological parameters* - Gas exchange - HR, BLa *Performance variables:* - Time at VVO_{2max} - Tlim	- PeakVO_2 was ↑during HIIT. - ↑ time running >90%VVO_{2max} during HIIT - HIIT resulted better than CR to stimulate aerobic metabolism with ↑Tlim, longer time at VVO_{2max} and obtaining ↑ peakVO_2 with lower BLa.
Billat et al. [49]	*n* = 7 males 51 ± 6 years 71 ± 4 kg 175 ± 5 cm VO_{2max} 52±6 ml/kg/min *Trained male athletes *50-70 km/wk	Repeated measures. All participants completed 3 HIIT in randomised order. *A field-based study (on a track)	Runs until exhaustion: i) $HIIT_1$: 15s runs alternating between 90-80% VVO_{2max} ii) $HIIT_2$: 15s runs alternating between 100-70% VVO_{2max} iii) $HIIT_3$: 15s runs alternating between 110-60% VVO_{2max}	*Physiological parameters* - Gas exchange (peak VO_2 and VO_{2max}). - HR and BLa *Performance variables:* - Time at VVO_{2max} - Tlim)	- In all HIITs, runners reached HR_{peak} and peakVO_2 - $HIIT_3$ ↑BLa, ↓distance at VVO_{2max}, and ↓total distance - $HIIT_1$ and $HIIT_2$: longer time at VO_{2max} - $HIIT_2$ ↑time HRmax, was performed at ↑velocity, and = or ↓ BLa.
Seiler et al. [50]	*n* = 12 (9 M, 3 F) 28 ± 5 years 68 ± 10 kg 176 ± 8 cm VO_{2max} 65 ± 6 ml/kg/min *Trained male *>4 years training (>3	Repeated measures. All participants completed 4 HIIT sessions in randomised order. *Laboratory conditions	The W:R was 1:1 and the total work at 24 min for each session. i) 24 x 1 min ii) 12 x 2 min iii) 6 x 4 min iv) 4 x 6 min *Self-selected running pace (as fast as possible)	*Physiological measurements:* - Gas exchange data - HR, BLa *Perceived exertion:* - RPE *Performance measurements:*	- Velocity ↓ increasing in duration - 24x1 obtained the ↓PeakVO_2 and the ↑VO_2 during recovery. No differences between the others. - HR and BLa = across HIITs (92-95% HRmax and 4.5 mM). - RPE was = (averaged 16-17). - Physiological response to short HIIT

	ss/wk)			- Running velocity	is different to HIITs lasting 2-6 min
O´Brien et al. [51]	*n* = 17 (14 M, 3 F) 22 ± 4 years 74 ± 11 kg VO_{2max} 57± 9 ml/kg/min *Moderately trained runners	Repeated measures. All participants completed 3 HIITs in a balanced random order. *Laboratory conditions	i) HIIT$_1$: 10x1-min at VVO_{2max} (1:1, resting at ½ VVO_{2max}) ii) HIIT$_2$: 5x2-min at VVO_{2max} (1:1, resting at ½ VVO_{2max}) iii) CR: 20-min at 75% VVO_{2max}	*Physiological measurements:* - VO_{2max}, VVO_{2max} and RER *Performance measurements:* - Time above VVO_{2max}	- HIIT$_1$ and HIIT$_2$ resulted in ↑VO_2 than CR with no differences between them - Time >90%VO_{2max} was ↑ in HIIT 1. No participant exceeded 90% VO_{2max} in CR.

↑: to increase or to obtain a higher value; ↓: to impair or to obtain a lower value; ~: approximately; = it means similar or identical values.

AOD: accumulated oxygen deficit; BMI: body mass index; BLa: blood lactate accumulation; EE: energy expenditure; EPOC: post-exercise oxygen consumption; HR: heart rate; LTP: lactate turn points; RE: running economy; RER: respiratory exchange ratio; VO_{2max}: maximal oxygen uptake.

CR: continuous run; HIIT: high-intensity intermittent training; RPE: rate of perceived exertion; T_{lim}: time to exhaustion sustained at VO_{2max}; V_{max}: maximal velocity of the graded maximal test; VVO_{2max}: velocity associated to VO_{2max}; W:R: work-to-rest ratio; VLTP: velocity associated to lactate turn points.

CMJ: countemovement jump; HS: handgrip strength test; SJ: squat jump.

Table 2. Studies (n= 8) examining the impact of HIIT-based running programme on physiological, metabolic, neuromuscular and biomechanics measurements in recreationally trained endurance runners.

Study	Subject description	Training programme (treatment and control groups)	Outcome measures	Results
Bangsbo et al. [10]	*n* = 17 males 34 ± 2 years 74 ± 2 kg 182 ± 2 cm VO_{2max} 63±2 ml/kg/min *Moderately trained male endurance athletes (running 4–5 days/wk)	- *Intervention period:* For a 6-9 week period. - *Groups:* speed endurance group (SIT, *n*=12) and control group (CG, *n*=5). - *Training:* *SET: 25% ↓ in the weekly training but including SIT (2-3 times/wk, 8–12 repeated 30-s running bouts at 95% of maximal speed with 3-min passive recovery), HIIT (4x4-min running at an ~85% of HR_{max} separated by 2 min of passive recovery), and 1-2 sessions of CR (75–85% of HR_{max}). *CG: continued the endurance training (~55 km/wk).	*Physiological measurements:* - VO_{2max} and RER - HR and blood samples (BLa and K+) - Muscle analysis: ion transport proteins and enzymes *Performance measurements:* - Incremental test. - Repeated sprint test. - 3-km and 10-km.	- The inclusion of SIT and HIIT with ↓ in training volume not only resulted in ↑ short-term work capacity but also ↑ 3- and 10-km performance in endurance runners. - The improvements were associated with an ~70% higher expression of Na^+-K^+ pump ẟ^2-subunit and lower plasma K^+ concentrations during exhaustive running.
Denadai et al. [15]	*n* = 17 males 37 ± 4 years 63 ± 4 kg 166 ± 5 cm VO_{2max} 59±6 ml/kg/min *Trained endurance runners training a mean weekly volume of ~80 km divided into 6 training sessions	- *Intervention period:* For 4 weeks - *Groups:* 95%VVO_{2max} or 100%VVO_{2max} groups - *Training:* 2 HIIT sessions per week (at 95-100% VVO_{2max}), 1 session at VLTP (2x20 min with 5 min of rest at 60%VVO_{2max}) and 3 CR (45–60 min at 60–70%VVO_{2max}): * 95% VVO_{2max}: 4 intervals (60% T_{lim} at 95%VVO_{2max}; recovery=30%T_{lim} at 50% VVO_{2max}) * 100%VVO_{2max} group: 5 intervals (identical to previous, but according to 100%VVO_{2max})	*Physiological measurements:* - VO_{2max} and RER - HR and BLa *Performance measurements:* - Incremental test - Submaximal test - 1,5 and 5 km time trials	-VVO_{2max}, RE, and performance (1.5 and 5 km) can be ↑ using a 4-week training program consisting of 2 HIIT sessions at 100% VVO_{2max} and 4 submaximal run sessions per week (the 95%VVO_{2max}) - CG did not present significant improvement on the VVO_{2max}, RE and 1.5 km running performance
Esfarjani et al. [14]	*n* = 17 males 19 ± 2 years 73 ± 3 kg 172 ± 4 cm VO_{2max} 51±2 ml/kg/min *Moderately trained male runners with 2-3 years of run training.	- *Intervention period:* For 10 weeks - *Groups:* 2 intervention groups (HIIT-based, EG_1 and EG_2) and 1 control group (CR-based, CG) - *Training:* * HIIT groups (G_1 and G_2): 2 HIIT sessions and 2 CR (60 min at 75%VVO_{2max}) each week. $G_{1:}$ 5-8 intervals at VVO_{2max} for a duration equal to 60% T_{lim}, with a 1:1 W:R.	*Physiological measurements:* - VO_{2max} and RER - HR, BLa *Performance measurements:* - Incremental test - 3000 m time trial	- HIIT-based running plan ↑ 3-km running performance time (−7.3%), concomitant with ↑VO_{2max} (+9.1%), VVO_{2max} (+6.4%), T_{lim} (+35%) and V_{LT} (+11.7%). - SIT improved 3km performance (−3.4%) with simultaneous ↑ in VO_{2max} (+6.2%), vVO_{2max} (+7.8%) and T_{lim} (+32%), but not V_{LT} (+4.7%).

		G_2: 7-12 x 30s bouts at 130%VVO_{2max} with 4.5 min of recovery. * CG: 4x 60-min CR (75%VVO_{2max}) per week.		- ↑ performance and physiological variables tended to be greater using more prolonged HIIT at VVO_{2max} when compared with SIT
Gliemann et al.[13]	*n* = 160 *HIIT group:* *n* = 132 (58M, 74F) 49 ± 0.8 years 73 ± 1 kg VO_{2max} 52±1 ml/kg/min *Control group (CG):* *n* = 28 (15M, 13F) 46 ± 2 years 73 ± 2.5 kg VO_{2max} 52±4 ml/kg/min *Recreational >2 yr training (>3ss/wk)	- *Intervention period:* For 8 weeks - *Groups:* CG and HIIT group (replacing 2 of 3 weekly sessions with 10-20-30 training) - *Training:* * CG: same plan (CR-based, HR between 75% and 85% of HR_{max}) * HIIT group: 1x CR + 2x 10-20-30 training per week. (10-20-30: 3-4× 5-min running periods interspersed by 2-min of rest. Each 5-min running period consisted of 5 consecutive 1-min intervals divided into 30, 20, and 10 s at an intensity corresponding to ∼30%, ∼60%, and ∼90–100% of maximal running speed.	*Physiological measurements:* - VO_{2max} and RER - Blood pressure - HR, BLa - Blood variables: glucose, cholesterol, insulin, cortisol - Muscle morphology *Performance measurements:* - Test to exhaustion - 5000 m time trial	- 8 weeks of 10-20-30 training was effective in improving VO_{2max}, 5km performance (-38 s), and lowering blood pressure (∼5 mmHg). - Muscle fiber area, fiber type, and capillarization were not changed after 10-20-30 training.
Gunnarsson et al.[12]	*n* = 18 (12M, 6F) 33 ± 2 years 75 ± 3 kg 178 ± 2 cm VO_{2max} 52±1 ml/kg/min *Moderately trained runners (3-4 weekly running sessions, ~30 km/wk)	- *Intervention period:* For 7 weeks - *Groups:* CG and HIIT group (10-20-30 training) - *Training*: 10-20-30 training concept (identical to the previous) . * CG: continued with their regular endurance training (CR-based) * HIIT group: all regular training sessions were replaced with three weekly 10-20-30 training sessions. In the first 4 wk, 10-20-30 conducted 3x5-min intervals and, in the remaining 3 wk, 4x5-min intervals per session.	*Physiological measurements:* - VO_{2max} and RER - Blood pressure,HR, BLa - Blood variables: glucose, cholesterol, insulin, cortisol, - Muscle morphology *Performance measurements:* - Incremental test - 1.5-km and 5-km trials	- After 7-week of 10-20-30 training, with a ~50% ↓ in training volume, VO_{2max} ↑ by 4% and performance in a 1.5-km and a 5-km run ↑ by 21 and 48 s, respectively. - Fasting blood and plasma values = CG, while HIIT group ↓values at post-test in cholesterol and LDL. - Resting HR remained unchanged in both groups, but blood pressure was reduced in the HIIT group after intervention. - Muscle morphology = in both groups. The same occurred in BLa.
Smith et al.[17]	*n* = 27 25 ± 1.3 years 72 ± 2 kg 178 ± 2 cm VO_{2max} 61±1 ml/kg/min *Well-trained males endurance runners	- *Intervention period:* For 4 weeks - *Groups:* CG (n=9), $HIIT_1$ (60%T_{max}, n=9) and $HIIT_2$ (70%T_{max}, n=9). - *Training*: HIIT groups completed 2 HIIT ss/wk at VVO_{2max} and their respective T_{max} duration. A W:R of 1:2 was used during HIIT. Moreover, HIIT groups performed 1 CR (30-min at 60% VVO_{2max}) per week. * $HIIT_1$: 6 intervals per HIIT session	*Physiological measurements:* - VO_{2max}, RER, VT, and RE - HR and BLa *Subjective ratings:* -*S*leep, fatigue, stress and muscle soreness	- $HIIT_1$ showed a 17-s improvement in 3km, compared to a 7-s improvement of $HIIT_2$. This change in $HIIT_1$ was related to changes in VO_{2max} and RE, and these runners improved VT (6.8%) and T_{max} (50s) compared to 1.7% and 16-s improvements in $HIIT_2$.

		* $HIIT_2$: 5 intervals per HIIT session * CG: Maintained their current training level (low intensity-long duration training)	*Performance measurements:* - Treadmill test - 3-km and 5-km	
Vezzoli et al. [16]	*n* = 20 males *CR group:* 50 ± 6 years 69 ± 10 kg 174 ± 7 cm *HIIT group:* 45 ± 8 years 72 ± 9 kg 176 ± 6 cm *National level, 45 km/wk	- *Intervention period:* For 8 weeks - *Groups:* 2 groups, 3 times non consecutively per week: CR-based (n=10) or HIIT-based (n=10) - *Training*: 3 different types of training sessions were scheduled, with the total distance covered in each session being controlled: * CR: a) 64.5 min at 70% GET, b) 58.5 min at 80% GET, and c) 54 min at 90% GET. * HIIT: a) 18x(1 min at 120% GET, 2 min at 65%), b) 18x(1 min at 130% GET, 2 min at 65%), and c) 18x(1 min at 140% GET, 2 min at 65%).	*Physiological measurements:* - VO_{2max}, RER and VT - HR, BLa - Blood pressure *Indexes of oxidative stress in blood and urine samples*	- CR and HIIT induced similar beneficial effects in master runners, ↓resting levels of oxidative stress biomarkers - Resting lipid peroxidation levels were ↓ after training both in CR and HITT. - No changes in PC resting values in both CR and HITT. - The data showed ↓ (25%) in urinary 8-OH-dG excretion in both CR and HITT groups. - The defences against oxidative damage were lowered only in CR, not in HITT.
Zaton et al. [11]	*n* = 17 (6F, 11M) *CG:* 34 ± 15 years 70 ± 10 kg 174 ± 7 cm *EG:* 34 ± 9 years 76 ± 7 kg 176 ± 12 cm *Amateur long distance runners >1 year of experience	- *Intervention period:* For 8 weeks - *Groups:* 2 groups completing 8 weeks of CR-based (CG, n=9) or HIIT-based (EG, n=8) - *Training*: CG performed 3-4 CR ss/wk; EG performed 2 HIIT and 1 CR ss/wk. * CG: continued to train as normal * EG: HIIT, 4x 20–30 s repetitions of maximal intensity running (covering a distance of 90–200 m). Rest between each repetition was based on a 1:2 W:R and ranged from 40 to 60 s. The number of sets performed ranged 2-4.	*Physiological measurements:* - VO_{2max} - HR. - Blood variables during graded exercise test: BLa, pH, partial pressure of O2 and CO2 (pO2 and pCO2) *Performance measurements:* - Cooper test	- HIIT develops physiological function similar to a CR-based training protocol in amateur long-distance runners. - HIIT training ↑VO_{2max}, minute ventilation, tidal volume, distance covered in the Cooper test, and ↑ post-exercise recovery as well as RE. - CG ↑VO_{2max} and tidal volume with a larger ↓ in minute ventilation compared with EG - Relative VO_{2max} and relative HR ↓ in both groups, which suggests improved RE in both groups.

↑: to increase or to obtain a higher value; ↓: to impair or to obtain a lower value; ~: approximately; = it means similar or identical values.

AOD: accumulated oxygen deficit; BMI: body mass index; BLa: blood lactate accumulation; EE: energy expenditure; EPOC: post-exercise oxygen consumption; GET: gas exchange threshold; HR: heart rate; LTP: lactate turn points; RE: running economy; RER: respiratory exchange ratio; VO_{2max}: maximal oxygen uptake.

CR: continuous run; HIIT: high-intensity intermittent training; SIT: sprint interval training; RPE: rate of perceived exertion; T_{lim}: time to exhaustion sustained at VO_{2max}; T_{max}: time for which VVO_{2max} can be maintained; V_{max}: maximal velocity of the graded maximal test; VVO_{2max}: velocity associated to VO_{2max}; W:R: work-to-rest ratio; VLTP: velocity associated to lactate turn points; VT: ventilatory threshold

CMJ: countemovement jump; HS: handgrip strength test; SJ: squat jump.

Table 3. Physiotherapy evidence database scale (PEDro)

Study	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	**Total score**
Laffite et al. [55]	0	0	0	0	0	0	0	1	1	1	1	**4**
Vezzoli et al. [16]	1	0	0	1	0	0	0	1	1	1	1	**6**
Gunnarsson et al. [12]	1	0	0	1	0	0	0	1	1	1	1	**6**
Gliemann et al. [13]	1	0	0	1	0	0	0	1	1	1	1	**6**
Bangsbo et al. [10]	1	1	0	1	0	0	0	1	1	1	1	**7**
Denadai et al. [15]	1	1	0	1	0	0	0	1	1	1	1	**7**
Esfarjani et al. [14]	1	0	0	1	0	0	0	1	1	1	1	**6**
Smith et al. [17]	1	1	0	1	0	0	0	1	1	1	1	**7**
Zaton et al. [11]	0	1	0	1	0	0	0	1	1	1	1	**6**

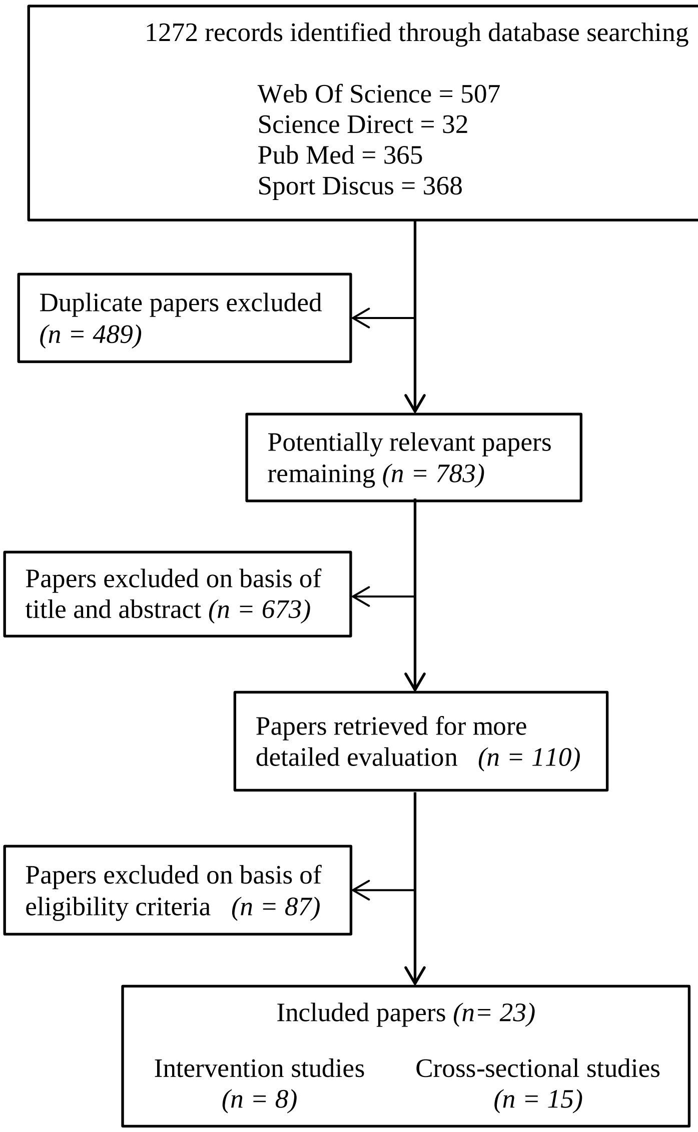

Figure 1. Flowchart illustrating the different phases of the search and selection of the studies.

2. ACUTE RESPONSE TO A TYPICAL HIGH-INTENSITY INTERMITTENT TRAINING PROTOCOL FOR ENDURANCE RUNNERS (PAPERS II, III AND IV)

Acute effects of extended interval training on countermovement jump and handgrip strength performance in endurance athletes: Postactivation potentiation

García-Pinillos Felipe, Soto-Hermoso Víctor M, Latorre-Román Pedro Á.

Journal of Strength and Conditioning Research, 29 (1): 11-21, 2015

ACUTE EFFECTS OF EXTENDED INTERVAL TRAINING ON COUNTERMOVEMENT JUMP AND HANDGRIP STRENGTH PERFORMANCE IN ENDURANCE ATHLETES: POSTACTIVATION POTENTIATION

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ABSTRACT

García-Pinillos, F, Soto-Hermoso, VM, and Latorre-Román, PA. Acute effects of extended interval training on countermovement jump and handgrip strength performance in endurance athletes: postactivation potentiation. *J Strength Cond Res* 29(1): 11–21, 2015—The purpose of this study was to analyze multiple effects of an extended interval training (EIT) protocol on countermovement jump (CMJ) and handgrip strength in endurance athletes and to determine the relationship between fatigue and potentiation. Thirty experienced sub-elite male long-distance runners (age = 28.26 ± 8.27 years, body mass index = 22.24 ± 2.50 $kg \cdot m^{-2}$, and $\dot{V}O_2max = 58.7 \pm 4.50\ ml \cdot kg^{-1} \cdot min^{-1}$) participated voluntarily in this study. Subjects performed the protocol on an outdoor running track, which consisted of 12 runs of 400 m, grouped into 4 sets of 3 runs, with a passive recovery of 1 minute between runs and 3 minutes between sets (4 × 3 × 400 m). During protocol, fatigue parameters (lactate, heart rate, and rate of perceived exertion) and performance parameters (CMJ, handgrip strength, and time spent in each 400-m run) were controlled. Analysis of variance revealed a significant improvement in CMJ ($p < 0.001$) throughout the protocol. Cluster analysis grouped according to whether potentiation was experienced (responders group, $n = 17$) or not (nonresponders group, $n = 13$) in relation to CMJ change from rest to fatigued condition at the end of activity. Responders group significantly improved ($p \leq 0.05$) the performance in CMJ, handgrip strength and time spent in each 400-m run. Results suggest that despite induced fatigue for EIT, trained subjects can maintain their strength and power levels and their work capacity. This fact would support the rationale that improvements in performance may be due not only to metabolic adaptations but also to specific neuromuscular adaptations. Therefore, the evaluation of power should be considered simultaneously with running performance when monitoring endurance athletes.

KEY WORDS vertical jump, long-distance runners, running exercises, monitoring training

INTRODUCTION

The term "postactivation potentiation" (PAP) refers to the phenomenon that significantly enhances muscular power and, consequently, performance as a result of previous muscular work (8,34). The PAP phenomenon is induced by a voluntary contraction, as conditioning activity (CA) and has been shown to increase power during subsequent contractions of the muscle fibers (2,25). In general, short-term gains on muscle performance after CA are thought to include phosphorylation of myosin regulatory light chains and increased recruitment of higher order motor units (2). After a CA protocol, mechanisms of muscular fatigue and PAP coexist, and so, subsequent power output and performance depend on the balance between these 2 factors.

The efficacy by which a CA can stimulate PAP mechanisms and acutely enhance muscular performance ultimately depends on several factors (7), including, but not limited to, training experience (18), rest period length (19,31), and the type, intensity and volume of the CA performed (30). These variables have not been standardized in past research, and as a result, evidence of the effects of CA on the performance of subsequent explosive activities is equivocal (24) and no precise consensus has been formed regarding the optimal acute conditioning mode protocol in recreationally training and athletic populations (34).

In general, PAP is expected to occur after evoked contractions and after near-maximum or maximum voluntary CA in power-trained athletes when performing explosive tasks, but after a run to fatigue, power performance is not supposed to improve (23). Nevertheless, previous studies indicate that not only explosive, short, and intense stimuli can be used as a CA but also submaximum and longer or prolonged exercises can cause PAP for subsequent activities (4,5,12,22,32). Vuorimaa et al. (33) reported changes in

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Table 1. Body composition (mean, *SD*), physical fitness (mean, *SD*), and daily training information (*n*, %) of participants.*

Age (y) Mean (*SD*)	Height (m) Mean (*SD*)	Body mass (kg) Mean (*SD*)	BMI ($kg \cdot m^{-2}$) Mean (*SD*)	$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$) Mean (*SD*)
28.26 (8.27)	1.75 (0.04)	68.16 (6.70)	22.24 (2.50)	58.7 (4.50)

Daily training			
Number of sessions per week, *n* (%)	Duration of training sessions (min), *n* (%)	Perceived performance state, *n* (%)	Training experience (y), *n* (%)
5, 5 (16.7%) 6, 12 (27.9%) 7, 12 (27.9%) 8, 1 (3.3%)	30–40 min, 1 (3.3%) 40–60 min, 11 (36.7%) +60 min, 18 (60%)	60–79%, 3 (10%) 80–100%, 27 (90%)	6–8 y, 3 (10%) 8–12 y, 9 (30%) +12 y, 18 (60%)

*BMI = body mass index.

coordination strategy in leg extension exercises performed after induced fatigue by long-distance running in elite athletes, suggesting a link between endurance training and PAP. Hamada et al. (16) indicated that endurance training causes, on one hand, a greater amount of phosphorylation of regulatory myosin light chains in slow fibers, and on the other hand, a greater resistance to fatigue, which would allow the prevalence of potentiation, and it would explain the PAP presence in endurance athletes. Similarly, twitch potentiation has also been observed in endurance-trained athletes in evoked contractions after continuous (4,5,22) and intermittent running bouts (33). Moreover, PAP has also been reported in endurance-trained athletes in jump performance after intermittent exercises (33), continuous running exercises (12,33), and incremental protocols (4,22,32).

Considering these previous studies, the effects of specific fatigue induced by running exercises on power performance and rapid and explosive force have been studied in long-distance runners. However, most of the studies have been conducted in laboratory or maximum field tests. To the best of the researchers' knowledge, no study exists that assesses induced fatigue with a common workload in endurance athletes (extended interval training, EIT), that is performed in an outdoor track (field test), and that shows effects on power and rapid force across vertical jump and handgrip strength performance. Therefore, the aims of this study were (a) to analyze acute effect of running exercises (EIT) on countermovement jump (CMJ) and handgrip strength in endurance athletes and (b) to determine the relationship between fatigue and potentiation in long-distance runners during EIT.

Methods

Experimental Approach to the Problem

This study analyzes the evolution of CMJ and handgrip strength performance in distance runners in an EIT. This allows a comparison to be done between performance at rest (unfatigued condition) and at different levels of exercise-induced accumulated fatigue (fatigued condition). Different parameters such as the rate of perceived exertion (RPE), peak heart rate (HRpeak), heart rate recovery (HRrec) and accumulated lactate were assessed. These parameters are monitored in recovery from the EIT.

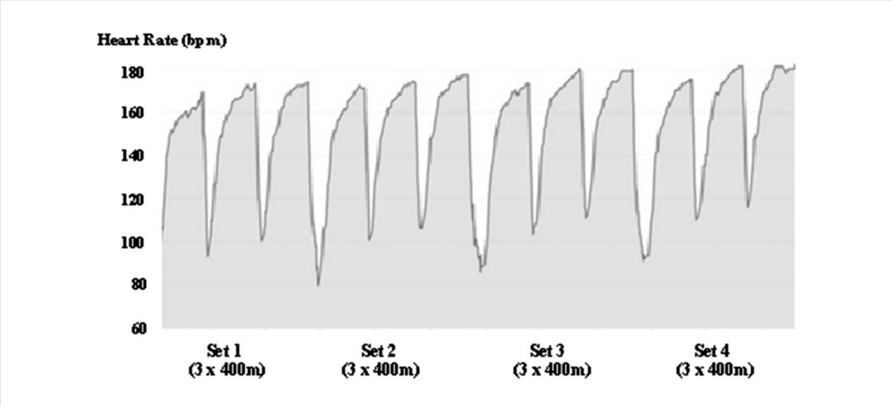

Figure 1. Training protocol, illustration based on heart rate response of the entire group.

Subjects

Thirty experienced recreational male long-distance runners, with a minimum experience of 6 years of training and competition (age range = 18–40 years old, mean age = 28.26 years, body mass index [BMI] = 22.24 ± 2.50 $kg\cdot m^{-2}$, and maximal oxygen consumption [$\dot{V}O_2max$] = 58.7 ± 4.50 $ml\cdot kg^{-1}\cdot min^{-1}$), participated voluntarily in this study. More information about participants is shown in Table 1. The study was conducted at the end of season 2012–13. The athletes trained regularly and had no history of injury in the 3 months before the study, which would limit training. After receiving detailed information on the objectives and procedure of the study, each subject signed an informed consent form to participate, which complied with the ethical standards of the World Medical Association Declaration of Helsinki (2008), and which made it clear that they were free to leave the study if they saw fit. The study was approved by the Ethics Committee from the University of Jaen (Spain) and was conducted following the European Community's guidelines for Good Clinical Practice (111/3976/88 of July 1990) and the Spanish legal framework for clinical research on humans (Real Decreto 561/1993 on clinical trials).

Procedures

Subjects were tested individually on 2 occasions. First, in a preliminary session, an anthropometric assessment and familiarization with CMJ and handgrip strength test were carried out. Anthropometric parameters were as follows: height (in meters) measured with a stadiometer (Seca 22; SECA Corp., Hamburg, Germany), body mass (in kilograms) recorded with a Seca 634, and the BMI (body mass [in kilograms]/height [in square meter]). Within the first session, the Léger's test was performed, through which $\dot{V}O_2max$ could be estimated (20), and which consisted of 20-m sprints with increasing speed in each run, indicating the pace with audible signals. $\dot{V}O_2max$ was calculated based on the speed that the participant reached in the last sprint through the following equation (20): $\dot{V}O_2$ (in milliliter per kilogram per minute) = 5.857 × velocity (in kilometer per hour) − 19.458.

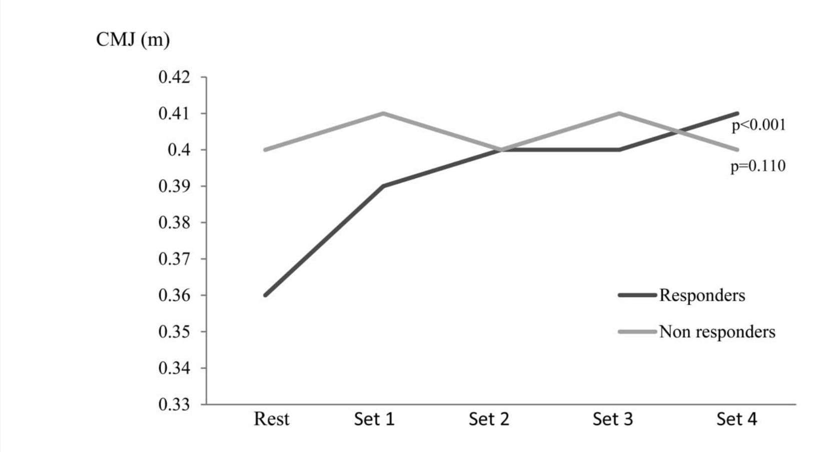

Figure 2. Changes in countermovement jump (CMJ) performance from rest condition to different moments throughout the extended interval training in athletes who did experience postactivation potentiation (responders group, RG) and those who did not experience it (nonresponders group, NRG).

The second session was performed 7 days after the preliminary session on an outdoor running track (lane 1) (temperature = 17.16 ± 5.81° C, relative air humidity = 62.65 ± 16.06%). Subjects were instructed to avoid strenuous exercise 72 hours before the training protocol. Before EIT, the athletes performed a warm-up, which consisted of 5–10 minutes of continuous running at a comfortable speed and 10 minutes of general exercises (high skipping, leg flexions, jumping exercises, and short bursts of acceleration). Then (pretest, unfatigued condition), the participants did 3 CMJs, separated by a 15-second recovery, which were then averaged, and 2 attempts of a 3-second handgrip, separated by 15 seconds of recovery, and the average of both hands was calculated. Next, the participants began the EIT protocol, which consisted of 12 runs of 400 m, grouped into 4 sets of 3 runs, with a passive recovery of 1 minute between runs and 3 minutes between sets (4 × 3 × 400 m) (Figure 1). Interval training widespread: it is used in the physical preparation of almost all endurance athletes (15,33) and is characterized by efforts lasting from 60 to 90 seconds with an intensity of 85–100% of maximal aerobic speed and with a high volume of bouts.

Between each 400-m run, the RPE on the Borg Scale (3) was recorded together with HRpeak and HRrec, using the Garmin Forerunner monitor 405 (Garmin International Inc., Olathe, KS, USA), time spent in each 400-m run (T_{400m}), and the handgrip strength of both hands (under identical conditions as those in the pretest). Moreover, between each set, the CMJ and blood lactate were also measured. The CMJ performance was recorded 2 minutes after the end of the last conditioning stimulus (the last 400 m of each set), obtaining consequently the CMJ performance in fatigued condition (set 1, set 2, set 3, and set 4). The CMJ was performed under identical conditions to the pretest (3 jumps separated by 15 seconds, and the average of the 3 was calculated). Blood lactate was recorded after the last run of each set, and for this purpose, a portable lactate analyzer Lactate-Pro (blood lactate in millimoles per liter; Arkray, Inc., Kyoto, Japan) was used. The measured time used in each set was the average of the 3 runs (T_{400m}).

During CMJ, the subjects were required to flex their knees to a 90° angle. Participants are experienced athletes who perform CMJ in their daily training sessions. Moreover, to make sure the execution of the CMJ is correct,

Table 2. Comparative analysis between RG ($n = 17$) and NRG ($n = 13$) in fatigue parameters (lactate, HRmax, HRrec, and RPE) and performance parameters (CMJ, Pforce, Ppower, ConcW, EccW, handgrip strength, and T_{400m}) in nonfatigued condition (at rest in CMJ and handgrip, and set 1 for the rest of variables), fatigued condition (set 4), and differences between both conditions (Δset 4-rest and Δset 4-set 1, respectively).*

	RG	NRG	*p*	RG	NRG	*p*	RG	NRG	*p*
Variables	Rest			Set 4			ΔSet 4-rest		
CMJ (m)	0.36 (0.06)	0.40 (0.04)	0.022	0.41 (0.07)	0.40 (0.04)	NS	0.05 (0.02)	−0.00 (0.01)	<0.001
Pforce ($N \cdot kg^{-1}$)	13.89 (3.58)	15.49 (3.40)	0.03	15.66 (3.31)	16.97 (4.04)	NS	1.77 (1.87)	1.47 (2.57)	NS
Ppower ($W \cdot kg^{-1}$)	24.48 (6.25)	27.25 (5.80)	NS	29.46 (7.86)	29.43 (5.67)	NS	4.98 (3.60)	2.18 (4.78)	NS
EccW ($J \cdot kg^{-1}$)	2.58 (0.60)	2.38 (0.69)	NS	2.45 (0.44)	2.19 (0.55)	NS	−0.13 (0.34)	−0.18 (0.51)	NS
ConcW ($J \cdot kg^{-1}$)	6.22 (1.02)	6.31 (0.93)	NS	6.52 (0.94)	6.01 (0.72)	NS	0.29 (0.47)	−0.29 (0.63)	0.004
Handgrip strength (kg)	40.56 (6.04)	43.31 (5.24)	NS	42.11 (8.75)	42.25 (5.36)	NS	1.55 (4.37)	−1.05 (1.89)	0.020
	Set 1			Set 4			ΔSet 4 − set 1		
T_{400m} (s)	77.58 (6.01)	73.33 (4.48)	0.014	75.90 (5.24)	75.02 (6.33)	NS	−1.68 (4.18)	1.69 (4.14)	NS
Lactate ($mmol \cdot ml^{-1}$)	9.73 (3.05)	11.09 (1.56)	NS	13.44 (2.46)	14.28 (2.16)	NS	3.70 (3.12)	3.19 (2.39)	NS
HRpeak ($b \cdot min^{-1}$)	176.95 (10.28)	175.18 (8.07)	NS	183.54 (10.70)	180.30 (8.41)	NS	6.58 (4.42)	5.12 (3.03)	NS
HRrec ($b \cdot min^{-1}$)	134.47 (16.11)	134.62 (12.64)	NS	155.15 (15.56)	154.89 (9.61)	NS	20.68 (7.42)	20.26 (9.35)	NS
RPE (6–20)	12.71 (2.15)	14.46 (2.06)	0.031	18.18 (1.21)	18.53 (0.51)	NS	5.47 (2.35)	4.07 (1.89)	NS

*RG = responders group; NRG = nonresponders group; CMJ = countermovement jump; NS = not significant; Pforce = peak force; Ppower = peak power; EccW = eccentric work; ConcW = concentric work; T_{400m} = time spent in each 400-m run; HRpeak = heart rate peak; HRrec = heart rate recovery; RPE = rate of perceived exertion.

TABLE 3. The evolution of results obtained from fatigue parameters (lactate, HRpeak, HRrec, and RPE) during EIT protocol broken down into different groups: the entire set of participants, the RG ($n = 17$), and NRG ($n = 13$), and the comparisons made post hoc (mean, *SD*) between the various groups.†

		Set 1	Set 2	Set 3	Set 4	*p*	Post hoc
Lactate (mmol·L^{-1})	Total group	10.36 (2.52)	12.69 (2.72)	13.78 (2.94)	13.83 (2.32)	<0.001	S1 < S2, S3 and S4***; S2 < S3*
	RG	9.73 (3.05)	12.83 (3.44)	13.39 (3.53)	13.44 (2.46)	0.003	S1 < S2, S3 and S4***
	NRG	11.09 (1.56)	12.53 (1.67)	12.24 (2.12)	14.28 (2.16)	<0.001	S1 < S3 and S4**; S2 < S3*
HRpeak (b·min^{-1})	Total group	176.19 (9.27)	179.03 (10.15)	180.30 (9.73)	182.14 (9.77)	<0.001	S1 < S2, S3 and S4***; S2 < S3** and S4***; S3 < S4***
	RG	176.95 (10.28)	179.85 (11.72)	181.71 (10.98)	183.54 (10.70)	<0.001	S1 < S2**, S3*** and S4***; S2 < S3** and S4***; S3 < S4***
	NRG	175.18 (8.07)	177.96 (7.98)	178.46 (7.85)	180.30 (8.47)	<0.001	S1 < S2*, S3** and S4***; S2 < S4*; S3 < S4***
HRrec (b·min^{-1})	Total group	134.53 (14.47)	145.03 (14.67)	150.98 (13.86)	155.04 (13.11)	<0.001	S1 < S2, S3 and S4***; S2 < S3 and S4***; S3 < S4***
	RG	134.47 (16.11)	144.77 (17.30)	151.48 (16.47)	155.15 (15.56)	<0.001	S1 < S2, S3 and S4***; S2 < S3 and S4***; S3 < S4***
	NRG	134.62 (12.64)	145.37 (11.01)	150.33 (10.11)	154.89 (9.61)	<0.001	S1 < S2, S3 and S4***; S2 < S3** and S4***; S3 < S4***
RPE (6–20)‡	Total group	13.47 (2.26)	15.25 (1.85)	16.91 (1.27)	18.34 (0.97)	<0.001	S1 < S2, S3 and S4***; S2 < S3*** and S4***; S3 < S4***
	RG	12.71 (2.15)§	14.77 (1.73)	16.71 (1.18)	18.18 (1.21)	<0.001	S1 < S2, S3 and S4***; S2 < S3*** and S4***; S3 < S4**
	NRG	14.46 (2.06)§	15.87 (1.88)	17.17 (1.39)	18.53 (0.51)	<0.001	S1 < S2**, S3** and S4**; S2 < S3** and S4**; S3 < S4**

*$p \le 0.05$, **$p < 0.01$, ***$p < 0.001$.

†EIT = extended interval training; RG = responders group; NRG = nonresponders group; S = set (S1, set 1; S2, set 2; S3, set 3; S4, set 4); HRpeak = peak heart rate; HRrec = heart rate recovery; RPE = rate of perceived exertion.

‡Friedman's test.

§Significant differences between RG and NRG ($p \le 0.05$).

TABLE 4. The evolution of results obtained from performance parameters (T_{400m}, CMJ, Pforce, Ppower, EccW, ConcW, and handgrip strength) during EIT protocol broken down into different groups: the entire set of participants, the responders group (RG, $n = 17$), and nonresponders group (NRG, $n = 13$), and the comparisons made post hoc (mean, *SD*) between the various groups.†

		Rest	Set 1	Set 2	Set 3	Set 4	*p*	Post hoc
T_{400m} (s)*	Total sample		75.74 (5.73)	75.12 (5.64)	75.91 (5.75)	75.52 (5.65)	0.448	
	RG		77.58 (1.31)‡	75.82 (1.37)	76.38 (1.41)	75.90 (1.39)	0.049	
	NRG		73.33 (1.50)‡	74.20 (1.57)	75.30 (1.61)	75.02 (1.59)	0.114	
CMJ (m)	Total sample	0.38 (0.05)	0.40 (0.05)	0.40 (0.06)	0.41 (0.06)	0.41 (0.05)	<0.001	Rest < S1* and S3** and S4***
	RG	0.36 (0.06)‡	0.39 (0.07)	0.40 (0.07)	0.40 (0.07)	0.41 (0.07)	<0.001	Rest < S1**, S2**, S3***, and S4***
	NRG	0.40 (0.04)‡	0.41 (0.04)	0.40 (0.04)	0.41 (0.04)	0.40 (0.04)	0.110	
Pforce ($N\cdot kg^{-1}$)	Total sample	14.58 (3.53)	15.47 (3.32)	15.73 (3.71)	16.26 (3.01)	16.23 (3.34)	<0.001	Rest < S2** S3** and S4*
	RG	13.89 (3.58)	14.94 (3.04)	15.47 (3.72)	15.97 (2.59)	15.66 (3.31)	0.001	Rest < S2** S3** and S4*
	NRG	15.49 (3.40)	16.16 (3.65)	16.07 (3.80)	16.63 (3.56)	16.97 (4.04)	0.276	
Ppower ($W\cdot kg^{-1}$)	Total sample	25.69 (6.22)	27.97 (5.42)	28.35 (5.62)	28.82 (5.54)	29.51 (6.99)	<0.001	Rest < S2* S3* and S4**
	RG	24.48 (6.25)	27.17 (5.95)	28.06 (6.35)	28.43 (6.13)	29.46 (7.86)	0.001	Rest < S2** S3* and S4***
	NRG	27.40 (6.03)	29.12 (4.58)	28.76 (4.63)	29.38 (4.79)	29.58 (5.89)	0.532	
EccW ($J\cdot kg^{-1}$)	Total sample	2.51 (0.64)	2.53 (0.63)	2.43 (0.52)	2.36 (0.54)	2.35 (0.50)	0.114	
	RG	2.58 (0.60)	2.55 (0.52)	2.49 (0.43)	2.46 (0.52)	2.45 (0.44)	0.766	
	NRG	2.42 (0.70)	2.51 (0.78)	2.34 (0.63)	2.22 (0.55)	2.22 (0.57)	0.141	
ConcW ($J\cdot kg^{-1}$)	Total sample	6.28 (0.98)	6.49 (0.97)	6.31 (0.85)	6.32 (0.93)	6.32 (0.89)	0.058	
	RG	6.22 (1.02)	6.45 (0.99)	6.39 (0.95)	6.40 (1.05)	6.52 (0.94)	0.121	
	NRG	6.36 (0.95)	6.55 (0.97)	6.20 (0.72)	6.21 (0.75)	6.04 (0.75)	0.033	S1 > S2* and S4*
Handgrip strength (kg)	Total sample	41.75 (5.78)	43.26 (5.98)	42.87 (5.96)	42.32 (6.71)	42.17 (7.36)	0.075	
	RG	40.56 (6.04)	43.18 (6.68)	42.61 (6.76)	42.17 (7.82)	42.11 (8.75)	0.005	Rest < S1** S2** S3* and S4*
	NRG	43.31 (5.24)	46.36 (5.20)	43.20 (4.98)	42.52 (5.20)	42.25 (5.36)	0.042	Rest < S1**; rest > S3*; S1 > S4**

*$p \leq 0.05$, **$p < 0.01$, ***$p < 0.001$.

†EIT = extended interval training; T_{400m} = time spent in each 400-m run; RG = responders group; NRG = nonresponders group; CMJ = countermovement jump; S = set (S1, set 1; S2, set 2; S3, set 3; S4, set 4); Pforce = peak force; Ppower = peak power; EccW = eccentric work; ConcW = concentric work.

‡Significant differences between RG and NRG ($p \leq 0.05$).

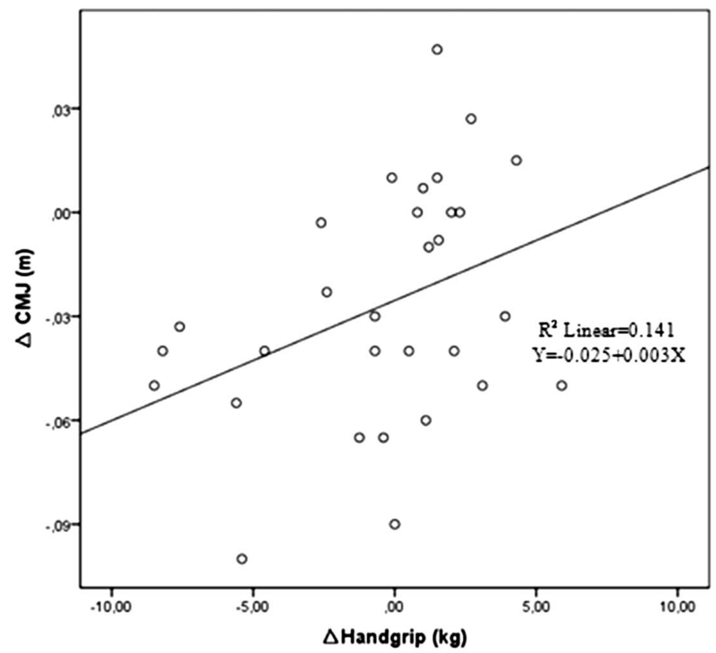

Figure 3. Scatterplot between ΔCMJ (difference set 4-rest) with ΔHandgrip strength (difference set 4-rest).

a familiarization session was carried out previously. The CMJ was recorded using the FreePower Jump Sensorize device (FreePower®, Sensorize srl, Rome, Italy), which was previously validated (26), and follows the following parameters (averaged from the 3 trials): maximum height of jump (in centimeter), peak force (Pforce; in Newton per kilogram), peak power (Ppower; in Watt per kilogram), eccentric work (EccW; in joule per kilogram), and concentric work (ConcW; in joule per kilogram). External mechanical work has been calculated using the variation of instantaneous total mechanical energy of the center of mass (6).

The handgrip strength test was performed considering the recommendations of previous studies (30). To record the handgrip strength (in kilogram), a digital hand dynamometer was used (TKK 5101 Grip D; Takey, Tokyo, Japan), adjusting the optimum grip through the calibration formula of Ruiz et al. (29). Participants were encouraged to achieve maximum handgrip strength.

Statistical Analyses

The data were analyzed by the statistics program SPSS version 19.0 for Windows (SPSS, Inc., Chicago, IL, USA) and the significance level was set at $p \leq 0.05$. The data are shown as descriptive statistics of mean and *SD*. The researchers used the Shapiro-Wilk test to verify normal distribution of data. The comparison of data between measures (at rest [pretest], set 1, set 2, set 3, and set 4) for the entire group was performed using a repeated-measures analysis (analysis of variance [ANOVA]) with post hoc Bonferroni's test. The researchers then performed the nonparametric contrast test of Friedman and Wilcoxon for those data in which no normal distribution was achieved after several transformations (square root transformation and logarithmic). Pearson's correlation between the increase from rest to set 4 and between set 1 and set 4 was used. Finally, the researchers performed a cluster analysis (*k*-means) grouped according to whether PAP was experienced (RG, responders group, $n = 17$) or not (NRG, nonresponders group, $n = 13$) in relation to CMJ change (ΔCMJ) from rest condition to postexercise accumulated fatigue (at the end of protocol, set 4). An analysis of covariance (ANCOVA) was performed between groups (RG and NRG) in all analyzed variables in nonfatigued condition (at rest in CMJ and handgrip strength, and set 1 for the rest of variables), and in posttest (fatigued condition at the end of EIT, set 4). In both analyses, covariables of age and BMI were considered. Also, ANCOVA was performed in post-pre difference (Δ), using the pretest as a covariable. The reliabilities of vertical jump (CMJ), handgrip strength, and blood lactate levels were assessed using intraclass correlation coefficients (ICCs) between test-retest and confidence interval (CI).

RESULTS

Test-retest reliability analysis of physical and physiological tests in the present study shows an ICC of 0.986 (95% CI = 0.972–0.993) for the CMJ, 0.963 (95% CI = 0.927–0.981) for the handgrip strength, and 0.974 (95% CI = 0.914–0.992) for blood lactate levels.

Cluster analysis was able to show the differences between those participants who experienced a significant level of PAP ($p < 0.001$) in the CMJ during the entire exercise session (RG; $n = 17$) and those participants who did not experience PAP ($p \geq 0.05$) in the CMJ (NRG; $n = 13$). The ANOVA performed between the 2 groups (RG and NRG) shows no significant differences ($p \geq 0.05$) in BMI (RG = 22.01 ± 2.39 $\text{kg}\cdot\text{m}^{-2}$, NRG = 22.65 ± 2.82 $\text{kg}\cdot\text{m}^{-2}$), $\dot{V}O_2$max (RG = 56.60 ± 3.24 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, NRG = 57.40 ± 3.10 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), or age (RG = 27.05 ± 7.22 years, NRG = 30.15 ± 9.92 years). Considering the difference in CMJ performance between rest condition and fatigued condition (from rest to the set 4, Δ), the ANCOVA revealed significant differences in ΔCMJ between both groups ($p < 0.001$), which produces an increase in RG (+5 cm, 13.89%) while NRG remained unchanged (Figure 2). In addition, significant differences ($p \leq 0.05$) are shown between RG and NRG in ΔConcW and ΔHandgrip strength, with post-pre differences of +0.29 and $-0.29\,\mathrm{J\cdot kg^{-1}}$ (4.66 and −4.6%, respectively) for ConcW and +1.55 and −1.05 kg (+3.82 and −2.42%, respectively) for handgrip strength. Finally, T_{400m} shows no significant difference between both RG and NRG (Table 2).

Table 3 shows the obtained results in repeated measures (ANOVA) for each one of the parameters used as fatigue parameters (Lactate, HRpeak, HRrec, and RPE). A significant increase ($p < 0.01$) in the registered values of each one of the above-mentioned parameters could be seen throughout the protocol. This increase exists not only in the entire group but also when observing the individual results of RG and NRG. No significant differences ($p \geq 0.05$) between RG and NRG were shown between set 1 and set 4, either in unfatigued or fatigued condition or between sets, except for RPE in set 1 ($p \leq 0.05$).

Table 4 presents obtained results in different repeated measures (ANOVA) for each one of the performance parameters assessed (T_{400m}, CMJ, Pforce, Ppower, ConcW, EccW, and handgrip strength) and post hoc Bonferroni's comparison intragroup to find significant differences in pairs of measures. Considering the entire group, significant changes were observed ($p < 0.001$) in CMJ, Pforce, and Ppower. Significant changes were seen for RG, T_{400m} ($p = 0.049$), CMJ ($p < 0.001$), Pforce ($p = 0.001$), Ppower ($p = 0.001$), and handgrip strength ($p = 0.005$). In contrast, for NRG only ConcW ($p = 0.033$) and handgrip strength ($p = 0.042$) changed significantly. The polynomial contrasts demonstrate that CMJ ($p = 0.001$), Pforce ($p < 0.001$), and Ppower ($p < 0.001$) are adjusted to linear function. This connection can be seen increasing during the training session. Also, an adjustment to quadratic function in handgrip strength ($p = 0.003$) was found.

For all participants involved ($n = 30$), the Pearson's correlation analysis between the different CMJ measures and the rest of analyzed variables was performed. Some significant correlations were found: CMJ with Ppower and CMJ with ConcW ($p < 0.01$) throughout the entire session (values for r, rest = 0.663 and 0.714; set 1 = 0.620 and 0.760; set 2 = 0.708 and 0.785; set 3 = 0.525 and 0.808; set 4 = 0.687 and 0.830, respectively). Also, a significant correlation was found between ΔCMJ with ΔHandgrip strength ($r = 0.375$, $p = 0.041$) (Figure 3).

Focusing on the created groups through cluster analysis (RG and NRG), it is convenient to note the correlation between ΔCMJ-Lactate and ConcW-Lactate. For RG, a positive correlation was found for both ($r = 0.535$, $p = 0.027$ and $r = 0.531$, $p = 0.028$, respectively), whereas for NRG, a negative correlation was found for both ($r = -0.782$, $p = 0.002$ and $r = -0.767$, $p = 0.006$, respectively).

DISCUSSION

The main finding of this investigation is the presence of PAP in CMJ of long-distance runners, during a field study based on classic intermittent training (EIT), a very common protocol for endurance athletes. However, the novelty of this study is not that the entire group experienced PAP, but rather that despite accumulated fatigued brought about by exercise and the fact that all athletes involved had similar characteristics–no significant differences ($p \geq 0.05$) concerning BMI, $\dot{V}O_2$max, and age–only some of the athletes boosted their performance in the CMJ during the protocol (RG). The performance of others remained unchanged (NRG). Moreover, the athletes performed the training protocol according to the criteria of intensity required. The evolutions of the descriptive parameters of fatigue indicate its increase throughout training protocol, reaching very high intensity levels in each one of them (RPE: 18.36 ± 0.97; HRpeak: 182.20 ± 9.62; HRrec: 155.43 ± 13.07; and blood lactate: 13.55 ± 2.41) and with no significant differences between RG and NRG. This fact eliminates and negates the possibility that PAP could be caused by athletes' level of involvement.

Previous studies have demonstrated PAP in different conditions. There is an abundance of literature on the subject of PAP in sprint or vertical jump using exercises with external loads or resistance like CA (6,16,32,34). However, to the best of the researchers' knowledge to date, a limited number of studies have investigated running exercises to elicit PAP in explosive movements such as CMJ. Boullosa and Tuimil (4) and Boullosa et al. (5) showed PAP in CMJ after incremental field running test. Vuorimaa et al. (33) found PAP in CMJ after 3 different running exercises (intermittent, continuous, and until fatigue), although tests were performed on a treadmill. Therefore, current research is novel because of its focus on PAP phenomenon in specific abilities like vertical jump, during actual and widespread field training session.

Looking at the data obtained for the entire group, PAP in CMJ was produced (+3 cm, 7.89%; $p < 0.001$) based on significant improvement in Ppower and Pforce ($p < 0.001$), whereas the rest of mechanical parameters associated to CMJ, like EccW and ConcW, remained unchanged ($p \geq 0.05$). Focusing on CMJ improvement, controversial data were found in similar studies. Boullosa et al. (5) reported an improvement of 4.9% in CMJ after the incremental running test while Boullosa and Tuimil (4) pointed out an increase of 12.7% in a similar, previous study. Vuorimaa et al. (33) obtained an improvement very similar to this study's data +8.9% in CMJ. Just as Boullosa et al. (5) indicated, it is difficult to compare results with previous studies because of the influence of the method used in PAP magnitude. Regarding mechanical parameters, the obtained results in the present study confirm the idea of PAP as a measure of CMJ performance and is therefore highly related to Ppower (5). In this study, the significant correlations found between CMJ-Ppower throughout the entire session support this rationale.

As for the rest of assessed parameters in this study, no significant changes were produced ($p \geq 0.05$) nor in the handgrip strength or in the T_{400m}, despite induced fatigue for the training protocol, as mentioned previously.

Considering the results obtained by the entire group, the maintenance of T_{400m} despite high values of fatigue registered would be another indicator of high involvement in the participants. The maintenance of handgrip strength, even showing a trend to increase indicates the importance of central mechanisms in maintaining a certain level of force (9). Central fatigue induced by exercise is manifested by a decrease in muscle activation (28). In this regard, the decreased muscular force in those muscles not involved in the exercise reveals supraspinal fatigue (13,23). Other authors (18,21), to check whether supraspinal fatigue occurs after prolonged exercise, noted the absence of changes in the force of muscles not involved in a prolonged running exercise through measuring handgrip, which leads the authors to conclude that selective supraspinal fatigue does not occur in this type of exercise. Supporting this line of thought, Millet and Lepers (23) hypothesized that grip strength loss (muscles not involved) after running would be a good revealer of supraspinal fatigue.

Based on previous studies (4,5) and for a better understanding of the results obtained, the researchers decided to incorporate cluster analysis because members of the same cluster are likely to have more similar responses. Two clusters of endurance athletes were obtained from the different magnitude of the CMJ. As mentioned above, these clusters were categorized as responders (RG, $n = 17$; CMJ = +13.89%) and nonresponders (NRG, $n = 13$; remained unchanged). From this analysis, RG confirmed an improvement of CMJ in fatigued condition by enhancement of Ppower and Pforce. Interestingly, this group also experienced a significant increase in handgrip strength (+1.55 ± 4.37 kg, $p = 0.05$) and T_{400m} performance (−1.68 ± 4.18 seconds, $p = 0.049$). In contrast, for NRG, a significant reduction in handgrip strength was shown (−1.05 ± 1.89 kg, $p = 0.042$) along with no significant trend to impair T_{400m} performance (+1.69 ± 4.14 seconds). In relation to the mechanical parameters of CMJ, the main difference is in ConcW, which was seen to affect fatigue in contrary ways across both groups (+4.66% RG and −4.6% NRG), thereby reinforcing the conclusion obtained by other authors (4,5) of the negative influence of local fatigue on the capability of athletes to demonstrate PAP during power performance. All this could indicate that performance in endurance exercise routines is largely conditioned by the muscular adaptations that allow an optimal application and maintenance of force. This is a controversial topic and previous studies (4,5) suggest that participants suffer a smaller loss of Pforce during CMJ and therefore could maintain the overall mean power and improve the subsequent Ppower. The results obtained in this study support this rationale and that the RG is less affected by fatigue as the NRG in all mechanical parameters of CMJ analyzed (Ppower, Pforce, ConcW, and EccW), although only a significant difference ($p = 0.004$) between both RG and NRG in ConcW was shown.

Concerning handgrip strength, Racinais et al. (27) provided similar data to this study's findings in respect to an improvement in fatigued condition, but the authors concluded that grip strength does not change significantly during continuous or intermittent exercise. In this study, the impairment in handgrip performance in NRG and its significant increase in RG may be because of an increase in neural activity in this type of intermittent exercise. It has been suggested that the central nervous system is capable of partial recovery within a few seconds in this type of exercise (1,13). This is contrary to the contributions of previous studies (21,23) indicating that there is a reduction of maximum voluntary activation in prolonged efforts. As indicated in the study by Martin et al. (21), the ability of the central nervous system to activate muscles to the maximum may be altered only in continuous exercise. Millet and Lepers (23) also found no changes in handgrip strength after a 30-km race, concluding that this measure cannot lead to the conclusion that there is no selective supraspinal fatigue. However, in line with some authors (1,13,27), the researchers find it convenient to make this simpler type of measure to explore the possible existence of supraspinal fatigue after endurance exercise and its relationship to the phenomenon of potentiation.

As indicated in the study by Skof and Strojnik (32), PAP is possible despite high concentrations of lactate, and this study confirms that rationale, obtaining RG values very high in blood lactate ($13.12 \pm 2.55\ \text{mmol}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). The significant correlation in RG between ΔLactate with ΔCMJ ($r = 0.535$, $p = 0.027$) is also worth noting. These results support those obtained by other researchers (17) who observed that subjects who tend to jump higher were those who were able to accumulate more lactate. Vuorimaa et al. (33) obtained different results for this correlation according to the run protocol carried out: a positive correlation in the intermittent running protocol (100% velocity associated with $\dot{V}O_2$max) ($r = 0.62$, $p < 0.01$) and a lack of correlation in continuous running (80% velocity associated with $\dot{V}O_2$max), although the improvements in CMJ are significant ($p < 0.001$) before and after both exercises. Similar findings where CMJ increases or remains at the same level have been researched during the early stages of an intermittent anaerobic test where blood lactate levels increased significantly above resting levels but not to maximum levels (10,17,22). Therefore, in intermittent running, the increase in the intensity of the exercise and blood lactate concentration seems to be associated with greater explosive force in long-distance runners.

However, for NRG, the correlation of ΔLactate with ΔCMJ was negative ($r = -0.782$, $p = 0.002$), which is to say the opposite of those results obtained for RG. This fact could be one of the reasons that some athletes experienced PAP and others did not, despite doing the same training protocol and having similar level of training, experience, and other characteristics. Numerous contrasting views exist regarding the physiological effects of lactate and its roles postproduction. There is, however, a clear association between the production of lactate and muscular fatigue (11). Muscle is now considered a consumer of lactate (11,14). The rate at which lactate is used is dependent on the rate of metabolism, blood flow, lactate concentration, hydrogen ion concentration, fiber type, and exercise training (14), which leads the researchers to believe that more research is needed to check whether some of these parameters could explain the presence or absence of PAP in athletes of similar level.

In conclusion, the effect of induced fatigue for an EIT protocol on vertical jump performance and handgrip strength shows that trained subjects can maintain their strength and power levels and, therefore, their work capacity. However, all athletes did not respond in the same manner to the exercise performed and this suggests that improvements in long-distance runners' performance after a training period may be due not only to metabolic adaptations but also to specific neuromuscular adaptations. Furthermore, the evaluation of power at the same time as running performance should be considered for the monitoring of endurance athletes.

Practical Applications

From a practical point of view, the PAP responses are different in each subject and it would be advisable for these tasks to be individualized, with a rest period for each subject as suggested by different authors (2,8). In this sense, more longitudinal research is needed, which would control the presence of PAP at different moments in a training season. These studies should focus on the PAP phenomenon as an instrument used to control neuromuscular adaptations during resistance training. Postactivation potentiation obtained in this study has a mechanical explanation, but neither the molecular basis nor neuromuscular parameters were directly explored, so additional studies may need to address these issues.

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Acute physiological and thermoregulatory responses to extended interval training in endurance runners: Influence of athletic performance and age

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Section III – Sports Training

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Acute Physiological and Thermoregulatory Responses to Extended Interval Training in Endurance Runners: Influence of Athletic Performance and Age

by
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This study aimed to describe the acute impact of extended interval training (EIT) on physiological and thermoregulatory levels, as well as to determine the influence of athletic performance and age effect on the aforementioned response in endurance runners. Thirty-one experienced recreational male endurance runners voluntarily participated in this study. Subjects performed EIT on an outdoor running track, which consisted of 12 runs of 400 m. The rate of perceived exertion, physiological response through the peak and recovery heart rate, blood lactate, and thermoregulatory response through tympanic temperature, were controlled. A repeated measures analysis revealed significant differences throughout EIT in examined variables. Cluster analysis grouped according to the average performance in 400 m runs led to distinguish between athletes with a higher and lower sports level. Cluster analysis was also performed according to age, obtaining an older group and a younger group. The one-way analysis of variance between groups revealed no significant differences ($p \geq 0.05$) in the response to EIT. The results provide a detailed description of physiological and thermoregulatory responses to EIT in experienced endurance runners. This allows a better understanding of the impact of a common training stimulus on the physiological level inducing greater accuracy in the training prescription. Moreover, despite the differences in athletic performance or age, the acute physiological and thermoregulatory responses in endurance runners were similar, as long as EIT was performed at similar relative intensity.

Key words: *training prescription, long-distance runners, high-intensity intermittent training.*

Introduction

Taking into consideration that success in endurance running involves both aerobic and anaerobic metabolism (Brandon and Boileau, 1992), endurance runners use different training methods (Hawley et al., 1997; Rabadán et al., 2011). As mentioned by Midgley et al. (2007), endurance runners often seek the most effective training methods to enhance performance, however, the most effective method is not always the healthiest one. The incidence of running-related injuries on an annual basis is high, occurring in 40-50% of runners (Fields et al., 2010) and, although it is widely accepted that injuries in endurance runners are multifactorial, it is also well known that running-related injuries are often attributable to training errors (Nielsen et al., 2012). The knowledge about every possible effect of a particular training protocol on the athlete plays a key role in the proper training prescription, which means that a further description of the impact of most typical running exercises on endurance runners is necessary.

As for the physiological response, abundant information is available, even though most scientific papers have focused on acute response to continuous running exercise from

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distances as short as 400 or 1600 m (Canfield et al., 2013), to long-distance running as a half-marathon (Piacentini et al., 2014). However, to the best of our knowledge only a few studies have analysed the physiological impact of intermittent training in runners (Gorostiaga et al., 2010; Vuorimaa et al., 2000), but none of them has worked with endurance runners during field-based extended interval training (EIT).

Regarding the thermoregulatory response, in spite of being well known the influence of core temperature (Tc) on athletic performance (Drust et al., 2005), to date, there is a lack of literature reporting the evolution of Tc during an intermittent running exercise in endurance runners.

Taking the above information into account, this study focused on the acute physiological and thermoregulatory responses to a common running exercise in endurance athletes. Therefore, the main objectives of this study were: i) to describe the acute impact of extended interval training (EIT) at physiological and thermoregulatory levels, and ii) to determine whether athletic performance and age influence acute physiological responses in endurance runners.

Material and Methods

Participants

Thirty-one recreational male endurance runners, with a minimum experience of 6 years of training and competition (age = 28.26 ± 8.27 years, body mass index [BMI] = 22.24 ± 2.50 kg/m^2, and maximal oxygen uptake [VO_{2max}] = 58.7 ± 4.50 ml·kg^{-1}·min^{-1}), voluntarily participated in this study. Most participants performed 6-7 running workouts per week, lasting more than 60 min. The athletes trained regularly and had no history of injury in the 3 months before the study. More information about the participants is shown in Table 1. The study was conducted during the competitive season.

After receiving detailed information on the objectives and procedures of the study, each subject signed an informed consent form to participate, which complied with the ethical standards of the Declaration of Helsinki (2013). The subjects could withdraw from the study at any point. The study was approved by the Ethics Committee of the University of Jaen (Spain) and was conducted following the European Community's guidelines for Good Clinical Practice (111/3976/88 of July 1990) and the Spanish legal framework for clinical research on humans (Real Decreto 561/1993 on clinical trials).

Procedures

Subjects were tested individually on 2 occasions. First, during a preliminary session, an anthropometric assessment and an incremental running test were carried out. The following anthropometric variables were evaluated: body height (m) measured with a stadiometer (Seca 222; Hamburg, Germany), body mass (kg) recorded with a Seca 634 scale (Hamburg, Germany), and the BMI (body mass [kg]/ height [m^2]). As for the running test, the Léger test (Léger et al., 1988) was performed, through which VO_{2max} could be estimated and which consisted of 20 m sprints with increasing speed in each run, indicating the pace with audible signals. The VO_{2max} was calculated based on the speed that the participant reached in the last sprint through the following equation (Léger et al., 1988): VO_2 (ml·kg^{-1}·min^{-1}) = 5.857 x velocity (km/h) - 19.458.

The second session was performed 7 days after the preliminary session on an outdoor running track (lane 1) (temperature = 17.16 ± 5.81 ºC, relative air humidity = 62.65 ± 16.06%). Subjects were instructed to avoid strenuous exercise 72 hours before the training protocol. The runners were free to drink water during the running protocol. Before EIT, the athletes performed a warm-up, which consisted of 5–10 min of continuous running at a comfortable speed and 10 min of general exercises (high skipping, leg flexions, jumping exercises, and short bursts of acceleration). Then the participants began the EIT protocol, which consisted of 12 runs of 400 m, grouped into 4 sets of 3 runs, with a passive recovery period of 1 min between runs and 3 min between sets (4 x 3 x 400 m). Interval training is used in the physical preparation of almost all endurance athletes (Gorostiaga et al., 2010; Vuorimaa et al., 2006) and is characterized by efforts lasting from 60 to 90 s with an intensity of 85–100% of maximal aerobic speed and with a high volume.

Between each 400 m run, the rate of perceived exertion (RPE) on the Borg Scale (Borg, 1982) was recorded together with the peak heart rate achieved and the recovery heart rate at 1 min (HRpeak and HRrec, respectively), using the

Garmin Forerunner monitor 405 (KS, USA). As indicated by Daanen et al. (2012), although the HRrec is generally expressed in absolute terms (bpm), it may be useful to express it relatively to the HRrec (ie, the difference between resting and maximal heart rate) to minimize interpersonal differences. Based on this, the difference between the HRpeak and HRrec at 1 min was calculated and was called heart rate reserve (HRR, in bpm). Also the tympanic temperature as an index of Tc (Brandon and Boileau, 1989; Roth et al., 1996) was recorded after each run. For this purpose, an infrared tympanic thermometer (ThermoScan® IRT 6020, Braun™, Germany) was used according to the manufacturer's guidelines. This device had been previously used and found reliable (Kocoglu et al., 2002). The time to cover each 400 m run (s) was also recorded although the time used for subsequent analysis was the average of the whole EIT protocol (T400m). Moreover, blood lactate (BLA, mmol.l^{-1}) was recorded after the last run of each set, and for this purpose, a portable lactate analyzer Lactate-Pro (Arkray, Inc.) was used.

Statistical Analysis

Descriptive statistics are represented as mean (SD), as well as percentages (%). Tests of normal distribution and homogeneity (Kolmogorov-Smirnov and Levene's) were conducted on all data before analysis. Analysis of repeated measures (ANOVA) was performed comparing the scores in analyzed variables throughout EIT. A Pearson correlation analysis between the increments (12th run – 1st run) of analyzed variables was used. Finally, k-means clustering was performed according to the T400m performance, and another according to the age of participants. Analysis of covariance (ANCOVA) was performed between the created groups, using VO_{2max} and the BMI as covariates. The level of significance was set at $p<0.05$. Data analysis was performed using SPSS (version 21, SPSS Inc., Chicago, Ill).

Results

Figure 1 shows the results obtained in the variables analysed throughout EIT (4x3x400 m). Significant differences were found in the RPE ($p<0.001$), Tc ($p=0.004$), the HRpeak and HRrec ($p<0.001$), and BLA ($p=0.012$) while the HRR remained unchanged ($p=0.231$).

The cluster analysis performed according to the T400m (Table 2) leads to distinguish between athletes with a higher sports level (HLG, T400m=73.07 s, n=23), and those with a lower one (LLG, T400m=84.91 s, n=8). The one-way analysis of variance reveals that both HLG and LLG show significant differences ($p<0.001$) in VO_{2max}. Nevertheless, the results obtained show that no significant differences were observed in the remaining variables considered. A cluster analysis was also performed according to the age of participants (Table 2), obtaining an older group (OG, age=38.50, n=10) and a younger group (YG, age=23.52, n= 21). The same statistical procedure was used and significant differences between the OG and YG were found only in the BMI ($p= 0.006$) and VO_{2max} ($p= 0.030$).

The Pearson correlation analysis performed for the whole group (n=31) between the increases of analysed physiological variables (Δ, results obtained in the first 400 m run – results obtained in the last 400 m run) and the rest of monitored variables (T400m, age, BMI and VO_{2max}) shows a significant correlation ($r=0.503$, $p=0.004$) between ΔHR and ΔHRrec, as well as a significant and negative correlation between ΔHRrec and the ΔHRR ($r=-0.832$, $p<0.001$). Besides, age correlates significantly with the BMI ($r=0.611$, $p<0.001$) and VO_{2max} ($r=-0.497$, $p=0.004$), while T400m correlates with VO_{2max} ($r=-0.799$, $p<0.001$).

Discussion

One of the aims of this study was to describe the impact of EIT (typical workout for endurance runners) on a physiological and thermoregulatory level. As pointed out in the introduction, training prescription´s errors play a key role in the high incidence rate of running-related injuries (Fields et al., 2010). Therefore, a further knowledge about the acute response to the most common running exercises is needed, and it will lead to a better understanding of the impact of each training stimuli on endurance runners, improving the accuracy in the training prescription. As far the authors know, no previous studies had focused on describing the evolution of physiological variables during field-based EIT in recreationally trained endurance runners. In this regard, the results obtained in the current study provide a detailed description (run by run) of commonly used variables in daily activity for athletes and coaches such as the RPE, heart rate (HRpeak, HRrec and HRR) or BLA, and one more variable not widely used but could be measured easily during any type of training with endurance runners i.e. the Tc.

Table 1

Body composition (mean, SD), physical fitness (mean, SD) and daily training information (n, %) of participants.

Age (y) M (SD)	Body heigth (m) M (SD)	Body mass (kg) M (SD)	BMI (kg/m^2) M (SD)	VO$_{2max}$ (ml·kg^{-1}·min^{-1}) M (SD)
28.26 (8.27)	1.75 (0.04)	68.16 (6.70)	22.24 (2.50)	58.7 (4.50)

Daily training							
Number of sessions per week n (%)		Duration of training sessions (min) n (%)		Perceived performance state n (%)		Training experience (y) n (%)	
5	6 (19.4%)	30-40 min	1 (3.3%)	60-79 (%)	3 (9.7%)	6-8 y	3 (10%)
6	12 (38.7%)	40-60 min	11 (36.7%)	80-100 (%)	28(90.3%)	8-12 y	9 (30%)
7	12 (38.7%)	+ 60 min	19 (60%)			+ 12 y	19 (60%)
8	1 (3.3%)						

BMI: body mass index

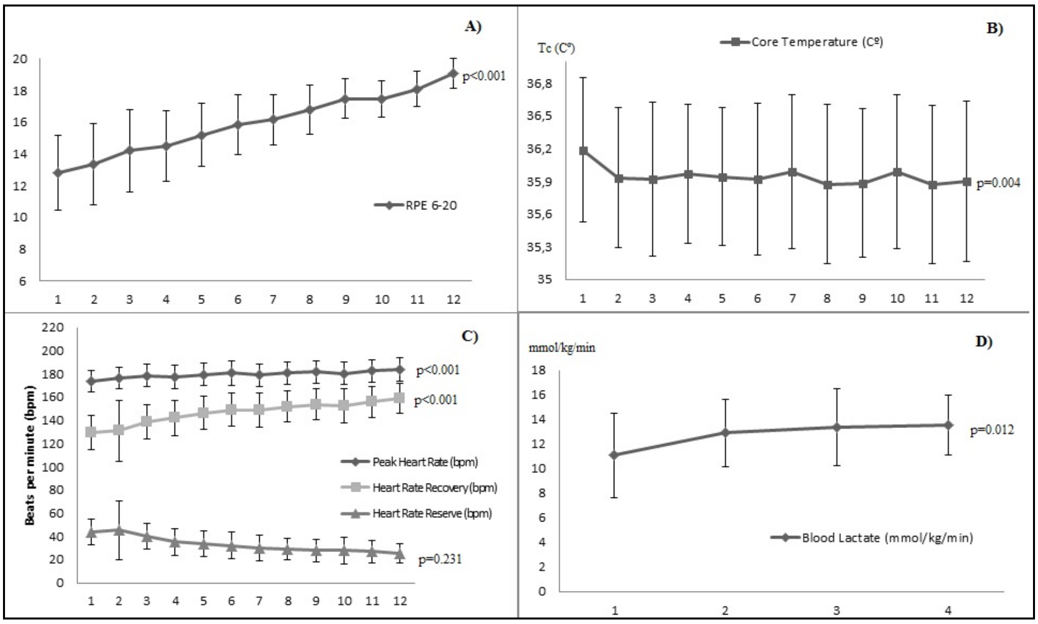

Figure 1

Changes of the analysed variables throughout extended interval training (4 x 3 x 400 m):
A) rate of perceived exertion in a 6-20 scale;
B) core temperature in Celsius degrees (ºC);
C) peak heart rate, heart rate recovery and heart rate reserve, all of them in beats per minute (bpm);
D) blood lactate in millilitre per kilogram per minute.

Table 2

Comparative analysis of physiological and thermoregulatory responses (mean, SD), in terms of increases and peaks reached, between the HLG and LLG, groups created according to the average performance in 400 m runs, and the OG and YG, groups created according to the age, as well as possible influence factors (BMI, VO2$_{max}$, age, T400m, and training experience).

Variables	HLG (n=23)	LLG (n=8)	*p value*	OG (n=10)	YG (n=21)	*p*
ΔRPE	6.27 (2.53)	6.25 (2.49)	0.992	6.80 (2.57)	6.00 (2.45)	0.410
ΔTc (ºC)	-0.33 (0.68)	-0.18 (0.53)	0.574	-0.12 (0.68)	-0.37 (0.61)	0.324
ΔHRpeak (bpm)	9 (5.78)	14 (5.01)	0.038	8.50 (4.97)	11.14 (6.28)	0.254
ΔHRrec (bpm)	28.74 (10.91)	29.13 (10.76)	0.932	26.60 (12.34)	29.90 (9.97)	0.431
ΔHRR (bpm)	-19.74 (1.92)	-15.13 (3.25)	0.231	-18.10 (11.70)	-18.76 (8.12)	0.856
ΔBLa (mmol·l^{-1})	2.13 (4.68)	3.50 (2.44)	0.439	2.90 (1.94)	2.29 (4.99)	0.712
HRpeak (bpm)	183.30 (8.73)	184.75 (13.71)	0.725	176.71 (10.64)	187.01 (7.50)	0.004
Peak BLa (mmol·l^{-1})	13.96 (2.28)	12.35 (2.52)	0.103	13.22 (2.19)	13.71 (2.55)	0.606
BMI	21.64 (1.82)	23.13 (3.37)	0.136	23.63 (2.42)	21.27 (1.94)	0.006
VO2$_{max}$ (ml·kg^{-1}·min^{-1})	58.05 (2.09)	53.03 (3.20)	<0.001	54.95 (3.70)	57.62 (2.69)	0.030
Age (y)	27.30 (7.73)	31.30 (10.20)	0.247	38.50 (4.71)	23.52 (4.60)	<0.001
T400m (s)	73.07 (3.62)	84.91 (5.91)	<0.001	77.40 (6.68)	75.51 (6.84)	0.473
Training experience (y)	7.17 (1.94)	6.63 (1.59)	0.480	7.80 (0.570)	6.67 (0.393)	0.113

HLG: higher level group; LLG: lower level group; OG: older group; YG: younger group; Δ: increase according to post-pre comparison; RPE: rate of perceived exertion; Tc: core temperature; HRpeak: peak heart rate; HRrec: heart rate recovery at 1 minute; HRR: difference between HRpeak and HRrec; BMI: body mass index; VO2$_{max}$: maximal oxygen uptake; T400m: average time in 400 m runs.

The physiological variables changed in a logical way, similarly to previous studies (Gorostiaga et al., 2010; Vuorimaa et al., 2006), increasing throughout the training protocol, reaching very high intensity levels in each one of them (RPE: 18.36 ± 0.97; HRpeak: 182.20 ± 9.62 bpm; HRrec: 155.43 ± 13.07 bpm; and BLA: 13.55 ± 2.41 mmol·l^{-1}). The high levels of BLA suggest that anaerobic glycolysis is extensively activated during these types of exercise, preferentially in type II muscle fibres (Green, 1978). There are numerous contrasting views of the physiological effects of lactate and its role on post exercise metabolism. On the one hand, there is a clear association between the production of lactate and muscular fatigue (Facey et al., 2013). High BLA is known to reflect a decreased muscle pH level and a concomitant fall in the force output of muscle contraction (Hultman and Spriet, 1986). On the other hand, muscle is now considered to be a consumer of lactate (Facey et al., 2013). As indicated by Brooks (2009), a relatively high BLA level (>10 mmol·l^{-1}) may also indicate high lactate consumption in working skeletal muscles, which may in fact enhance muscular performance. Anyway, BLA is of interest as it is considered to indirectly reflect the degree of anaerobic glycolysis activation (McCartney et al., 1986) and, consequently, the intensity of the previous work.

As for the thermoregulatory response, Tc showed a significant reduction throughout EIT, reaching immediately after the last 400 m run an average of 35.89 ºC. The results reported are opposing to previous studies which found an increase in Tc after different endurance races such as a half-marathon (Lee et al., 2010) or 4 km cross-country racing (Hunter et al., 2006). Probably, the fact that these studies were performed in a hot environment and data were collected during continuous running can explain this difference. Additionally, a wide variety of methods are available to measure Tc what makes the comparison of results difficult. Nevertheless, among the non-invasive sites for Tc measurement, tympanic temperature probably has the strongest association with Tc (Folk et al., 1998; Lee et al., 2010). To our knowledge, no previous studies had used intermittent running exercises under moderate environment with endurance runners. Just a few studies (Drust et al., 2005; Duffield et al., 2009) performed in dynamic sports allow for a comparison owing to the intermittent nature of these sport modalities. Both studies associated the increase in Tc with impairment in athletic performance, a situation not found in the current study in which the athletic performance, in terms of time required to complete 400 m runs, remained unchanged. As indicated by Moran and Mendal (2002), an increase in Tc during exercise results in overloading the cardiovascular and metabolic system. In a previous study, Pujol et al. (1994) found a decrease in Tc after a marathon in relation to resting values. The authors suggested that the lack of an increase in Tc during prolonged running could be an indicator of running economy, highly developed ability in endurance runners, and its relationship with the thermoregulation is not totally clear (Joyner et al., 2011). As concluded by Cheuvront and Haymes (2001) in a review, numerous individual and external factors can influence Tc, however, common consensus is lacking. Environmental conditions, dehydration and a metabolic rate, as well as gender, are commonly referenced as limiting factors in thermoregulatory control (Cheuvront and Haymes, 2001; Lee et al., 2010; Lim et al., 2008). In the current study, Tc baseline values at rest (pretest) were normal (36.43 ºC) (Folk et al., 1998) and, as earlier mentioned, the running exercise was conducted under moderate environmental conditions, so more research is needed on Tc in experienced athletes during intermittent exercise under different environmental conditions.

Determining whether athletic performance and age effect acute physiological and thermoregulatory responses in endurance runners was the other main purpose of this study. That is why the researchers decided to incorporate cluster analysis as members of the same cluster are likely to have similar responses. Regarding the first variable, athletic performance, two clusters of endurance athletes were obtained from the different magnitude of the T400 m performance (HGL and LLG). The major finding in this line was the fact that no significant differences between groups concerning physiological or thermoregulatory responses occurred. In this study, the HLG obtained VO_{2max} significantly higher than the LLG (+5.02 ml·kg-1·min-1), as well as a greater T400 m (11.84 s). Nevertheless, changes of the analysed variables throughout EIT do not show significant differences between the HLG and LLG. This means that the impact of EIT on the physiological level is the same, in spite of the differences in athletic performance, as long as the workout was performed at the same relative intensity and absolute load. No previous papers had been directly focused on this topic, however, some findings reinforce our results. Canfield and Gabel (2013) found that different distances runners (sprinters vs. endurance runners) did not differ in the HR or RPE after running two distances. In the same line, some previous studies had not observed a relationship between metabolic and physiological markers and performance during intermittent-sprint exercise (Duffield et al., 2009), or a football match (Krustrup et al., 2006).

With regard to the age effect, the major finding was the lack of differences in the physiological and thermoregulatory responses. At the same absolute load, both the OG and the YG showed similar responses, in spite of the difference in age (+14.98 years for the OG), VO_{2max} (-2.97 $ml\cdot kg^{-1}\cdot min^{-1}$), and the BMI (+2.36). Previous papers concluded that age could affect the HRpeak (Gellish et al., 2007), the HRrec (Daanen et al., 2012), while peak lactate levels remained unchanged (Nybo et al., 2014). The correlations obtained for the whole group between age, the BMI and VO_{2max}, as well as the inter-groups (OG-YG) differences in the HRpeak (OG: 176.71, YG: 187.01), support the above rationale. Nevertheless, the lack of differences between the OG-YG according to the behaviour of analysed variables throughout EIT allows to highlight that age is not a factor that influences the acute physiological and thermoregulatory response during EIT in experienced endurance runners.

Despite its exploratory nature, this study offers some insight into acute physiological and thermoregulatory responses to a typical workout for endurance runners and the influence of variables such as athletic performance and age. These findings are limited by the field-based nature of the present study which makes impossible to control some interesting factors as hydration status, and to standardise environmental conditions.

Conclusions

The obtained results provide a detailed description (run by run) of the physiological (HRpeak, HRrec, HRR, BLA, RPE) and thermoregulatory (Tc) responses to EIT in experienced endurance runners. The provided data help in understanding the impact of a common training stimulus on the physiological level leading to greater accuracy in the training prescription process. Moreover, despite the differences in athletic performance or age, the acute physiological and thermoregulatory responses in endurance runners are similar, as long as EIT is performed at similar relative intensity. The results suggest that the evaluation of physiological and thermoregulatory responses at the same time as running performance should be considered for monitoring of endurance athletes.

From a practical point of view, it seems quite difficult for recreational runners or coaches to afford including “gold standard” for physiological and thermoregulatory responses assessment in their daily activity. However, many athletic clubs can afford having devices as used in the current study. Hence, this study not only provides further knowledge about the impact of a typical training stimulus on endurance athletes, which plays a key role in improving performance and preventing injuries, but also includes easy-to-use tools for monitoring and controlling training adaptations in endurance runners.

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Do running kinematic characteristics change over a typical HIIT for endurance runners?

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Do running kinematic characteristics change over a typical HIIT for endurance runners?

Running head: Running kinematic during a HIIT

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Abstract

The purpose of this study was to describe kinematic changes that occur during a common high-intensity intermittent training (HIIT) session for endurance runners. Twenty-eight male endurance runners participated in this study. A high-speed camera was used to measure sagittal-plane kinematics at the first and the last run during a HIIT (3 x 4 x 400 m). The dependent variables were spatial-temporal variables, joint angles during support and swing, and foot strike pattern. Physiological variables, rate of perceived exertion and athletic performance were also recorded. No significant changes ($p \geq 0.05$) in kinematic variables were found during the HIIT session. Two cluster analyses were performed, according to the average running pace – Faster vs. Slower, and according to exhaustion level reached – exhausted vs. non-exhausted group (EG and NEG). At 1st run, no significant differences were found between-groups. As for the changes induced by the running protocol, significant differences ($p < 0.05$) were found between faster and slower athletes at toe-off in θHip and θKnee, while some changes were found in NEG in θHip during toe-off (+ 4.3º) and θKnee at toe-off (- 5.2º) during swing. The results show that a common HIIT session for endurance runners did not consistently or substantially perturb the running kinematics of trained male runners. Additionally, although some differences between groups have been found, neither athletic performance nor exhaustion level reached seems to be determinant in the kinematic response during a HIIT, at least for this group of moderately-trained endurance runners.

Keywords: fatigue-induced changes; interval training; long-distance runners; running technique

INTRODUCTION

Although there is no universal definition, high-intensity intermittent training (HIIT) generally refers to repeated short to long bouts of rather high-intensity exercise – performed close to 100% maximal oxygen uptake (VO_{2max}) - interspersed with recovery periods. HIIT is considered one of the most effective forms of exercise for improving the physical performance of athletes (3,4,8,32), and its effectiveness has been widely studied in endurance runners (16,21) compared to high-volume and moderate-intensity endurance training programmes.

Two facts support and reinforce the inclusion of HIIT into running plans for endurance runners: i) a greater training distance per week in runners is a risk factor for lower extremity running injuries (20) and, ii) a growing body of literature remarks the role of mean training intensity over a season for optimising the athletic performance (3,4,8,32). Nevertheless, coaches also need to be aware of the demands and risks of running faster, in terms of injury management and training prescription. It has been demonstrated that the impairment of performance resulting from muscle fatigue differs according to the types of contraction involved, the muscular groups tested, or the exercise duration and intensity (27). Compared with lower intensity cyclic workloads, intensive running requires activation of larger motor units with increased recruitment of fast oxidative and glycolytic muscle fibres, and the increase of the intensity of chemical processes in the muscle - increased metabolite concentration inhibits the activity of certain enzymes such as the sodium–potassium, calcium, and myosin ATPases - which exert a direct influence on the contractile ability of the muscle (34,39). Additionally, increases in running speed lead to higher impact forces imposed on the lower limbs (26) and greater levels of neuromuscular engagement (mainly in the hamstring muscles) (25). The concomitant increase in muscle acidity and decrease in phosphagen stores with muscle fatigue alters muscle force generation capabilities (9), which may be linked to changes in joint movement patterns (11,13,14,22,35) and in running mechanics (2), which are often linked to running injury (2,38). However, there is a lack of prospective studies evaluating injury occurrence so this is an important issue for future research.

The effect of exertion on running kinematics has been extensively studied (1,2,10,11,13,14,22,31,35). Some previous studies reported no alterations in running kinematic after different running exercises (1,11,23), whereas other works found fatigue-induced changes during running at kinematic level - i.e., increased hip extension (28), decreased knee flexion angle at foot strike (35), increase in step length with a corresponding decrease in cadence (22), and changes in foot strike pattern (30,31). However, most of these studies were performed in laboratory conditions and with athletes performing prolonged treadmill runs (14,22,35), or running-induced fatigue protocol on treadmills (1,9,13). The generalization of results from studies that analyse running on a treadmill may become controversial if treadmill and overground running biomechanics are not equivalent (18,37). In this sense, there is evidence showing differences when running on a treadmill and overground in several variables – stride frequency (37,40), contact time (18,37,40), ankle, knee, and hip kinematics (37,40), muscular activity (40), and plantar pressures (18). Just a few studies have been field-based (10,23,31), although all of them were focused on long-distance road racing. To the best of the authors' knowledge, just one study (11) has investigated the fatigue-induced changes in running patterns during interval running, although no kinematic parameters were measured during the interval workout, but in laboratory conditions running at previously fixed paces pre- and post-workout.

The main purpose of this study was to evaluate running kinematic characteristics during early and late stages of an actual and common HIIT for endurance runners. The authors hypothesised that certain running kinematic parameters would change between the first and last runs during a typical HIIT for endurance runners.

METHODS

Experimental approach to the problem

This is a single group repeated measures design in which the authors try to determine the fatigue-induced changes in running kinematic of endurance runners during a common HIIT protocol, performed on a track. For this purpose, a within-group comparison was performed, by considering fatigued and un-fatigued conditions – at the beginning and at the end of the protocol respectively. Additionally, the authors consider that kinematic alterations during the protocol can be influenced by athletic level and exhaustion level reached so that between-group comparisons were performed. Two facts justify this analysis: i) the effect of exertion on running kinematic is still unclear with some studies reporting no alterations (1,11,23), whereas other works found fatigue-induced changes during running at kinematic level (22,28,30,31,35), ii) some differences between faster and slower athletes have been reported by previous studies (10,31) in running kinematic alterations after long-distance races.

Subjects

Twenty-eight trained male endurance runners (age= 27±7 years, body mass= 68±5 kg; body mass index [BMI]= 22±1.7 kg/m^2, maximal oxygen uptake [VO_{2max}]= 59.7±3.3 ml·kg^{-1}·min^{-1}, and velocity associated to VO_{2max}

[VVO_{2max}]= 15.2±0.53 $km.h^{-1}$), voluntarily participated in this study. Inclusion criteria were: i) the participants were experienced athletes, with a minimum experience of five years on the training and competition; ii) the participants trained regularly (> 5 session/wk) and they had no history of injury in the previous three months that would limit training. The study was conducted during the competitive season.

After receiving detailed information on the objectives and procedures of the study, each subject signed an informed consent form to participate, which complied with the ethical standards of the Declaration of Helsinki (2013 version). The subjects could withdraw from the study at any point. The study was approved by the Ethics Committee from the University of Jaen (Spain) and was conducted following the European Community's guidelines for Good Clinical Practice (111/3976/88 of July 1990).

Procedures

Subjects were tested individually on two occasions. First, during a preliminary session, an anthropometric assessment and an incremental running test were carried out. The following anthropometric variables were evaluated: body height (m) measured with a stadiometer (Seca 222; Hamburg, Germany), body mass (kg) recorded with a Seca 634 (Hamburg, Germany), and the BMI (body mass [kg]/ height [m^2]). As for the running test, the Léger test (33) was performed, which consisted of 20-m sprints with increasing speed in each run, indicating the pace with audible signals. The VVO_{2max} was calculated based on the speed that the participant reached in the last sprint (5), and the VO_{2max} through the following equation (33): VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$) = 5.857 x velocity (km/h) - 19.458, with a correlation coefficient of 0.84 according to direct measures of VO_{2max}.

The second session was performed 7 days after the preliminary session on an outdoor running track (lane 1) (temperature = 17.1 ± 5.8 ºC, relative air humidity = 62.6 ± 16.1%). Subjects were instructed to avoid strenuous exercise 72 hours before the training protocol. The runners were free to drink water during the running protocol. Before HIIT, the athletes performed a standardised warm-up, which consisted of five minutes of low-intensity running and five minutes of general exercises (high skipping, leg flexions, lateral running, front and behind arm rotations, and 100-m incremental-intensity running bouts). Then, five 13-mm diameter retro-reflective markers (fifth metatarsal, lateral malleolus, lateral epicondyle of the femur, greater trochanter, and acromion) were placed on the right-side of the body (Figure 1). These landmarks defined the positions of upper body (head, arms and trunk being taken together), lower legs and feet. After markers placement, the participants began the running protocol, which consisted of 12 runs of 400 m, grouped into 4 sets of 3 runs, with a passive recovery period of 1 min between runs and 3 min between sets (4x3x400 m). Participants are experienced athletes who perform these types of workouts in their training programme. So the only instructions were to finish the protocols as fast as they could, maintaining a constant speed as much as possible. No more guidelines were provided as to exercise intensity, apart from the participants being informed that they were to exercise at an intensity of their own choice. This workout has been used by a previous study (19), and it is widely used in the physical preparation of endurance athletes (17).

FIGURE 1 ABOUT HERE

Materials and testing

Physiological variables: In order to monitor the physiological demands of this HIIT protocol, the cardiovascular response was monitored throughout the exercise, using the Garmin Forerunner monitor 405 (KS, USA). The peak heart rate achieved and the recovery heart rate at 1 min (HRpeak and HRrec, respectively) were used for the analysis. Additionally, blood lactate accumulation (BLa, mmol/l), and the rate of perceived exertion (RPE) were also recorded after the last run of the running exercise, and for this purpose, a portable lactate analyser (Lactate-Pro, Arkray, Inc.), and the 6-20 Borg Scale (6) were used.

Athletic performance: The time spent in each 400 m run (s) was also recorded. The variables used for subsequent analysis were the average running pace of the whole protocol ($km.h^{-1}$), and the impairment in the time spent (12th run – 1st run, ΔT400m, in seconds).

Kinematics: A sagittal-plane video (240 Hz) of the first and the last 400 m run during the protocol was recorded using a high-speed camcorder (Casio Exilim EXF1, Shibuyaku, Tokyo 151–8543, Japan). Videos were taken from a lateral view, with the camera perpendicularly placed five metres from the runner so that they could be filmed in the sagittal plane. Filming location was set at the end of the 400-m run, 20 metres before the finish line. For each runner, a complete stride cycle was captured on film, and kinematic variables were measured for the right leg – either during support or swing phase. Video data were analysed using a 2D video editor (VideoSpeed vs1.38, ErgoSport, Granada, Spain).

The dependent variables selected for the kinematics analysis are in accord with previous works (10,12,22,23,31) and are presented below:

i) Relative angle of the hip, knee and ankle (θhip, θknee and θankle, respectively) at three key points during support: (a) the initial contact (first visible point during stance where the athlete's foot clearly contacts the ground); (b) at mid-stance (the maximum knee flexion in the support phase); (c) at toe-off (the last frame with ground contact). Likewise, during swing, the θknee was controlled at the aforementioned key points (θknee at initial contact, mid-stance and toe-off), and θHip at toe-off was also measured during swing (10). θhip was defined as the sagittal plane angle between the trunk and thigh segments and was considered to be 180º in the anatomical standing position. The θknee was calculated as the sagittal plane angle between the thigh and leg segments and was also considered to be 180º in the anatomical standing position. The θankle was calculated in a counterclockwise direction using the leg and foot segments (22,23). For each variable controlled in this study, the 12^{th} run – 1^{st} run comparison was calculated and is shown as Δ (i.e. $\Delta\theta hip_1$).

ii) Spatial-temporal parameters: step length – distance from one foot strike to the next foot strike of the opposite foot (SL, in metres); and contact and flight time – the time duration from initial contact to toe-off, whereas flight time was the time duration from toe-off of one foot contact to the initial contact of the opposite foot (CT and FT respectively, in seconds).

iii) Foot strike pattern (FSP) at first contact with the ground, on a 1-5 scale of severity (31), from rearfoot to forefoot: 1) high rearfoot strike – landing with the second half of the heel (the landing from the back of the heel); 2) rearfoot strike – the ball of the foot landing before the heel; 3) midfoot – the landing of the heel and sole simultaneously; 4) forefoot – landing with the ball of the foot; 5) and high forefoot strike – the ball of the foot made contact with the ground (no contact with the heel, running on tiptoe).

Statistical Analysis

Descriptive statistics are represented as mean (SD), and percentages (%). Tests of normal distribution and homogeneity (Shapiro-Wilk and Levene's) were conducted on all data before analysis. Increase (Δ) of each variable as 12^{th} run – 1^{st} run comparison was calculated. Paired t-test was used to compare the analysed variables at the beginning and at the end of the HIIT protocol (1^{st} run vs. 12^{th} run) for the whole-group. As for the FSP, the equality of proportions, within-group (1^{st} and 12^{th} runs) and between-groups, was checked through McNemar test. A repeated measures analysis of variance (ANOVA), with post-hoc Bonferroni's test, was performed to examine possible differences in time spent in each 400 m run throughout the HIIT protocol. In order to determine the possible relationship between the athletic performance, the level of fatigue reached during the workout and fatigue-induced changes in running kinematics, a Pearson correlation analysis was carried out. Finally, k-means clustering were performed according to (i) the average running pace during the exercise, and (ii) the level of fatigue reached during the HIIT. Analyses of covariance (ANCOVA) were performed between the created groups – Faster vs. Slower, and EG vs. NEG, using the BMI as covariate. Reliability intra- and inter-observer was calculated for FSP (due to an observational method was used) using the Cohen's Kappa coefficient. The level of significance was set at $p<0.05$. Data analysis was performed using SPSS (version 21, SPSS Inc., Chicago, Ill).

RESULTS

Reliability intra-observer and inter-observer was calculated using Kappa of Cohen for FSP (intra-observer – Kappa = 0.904, proportion of agreement = 95%; inter-observer – Kappa = 0.834, proportion of agreement = 95%) (29).

The protocol was performed at 19.22 ± 1.38 km/h, with an intensity of ~125% of VVO_{2max} – according to data estimated from the Léger test. The repeated measures analysis showed no significant differences ($p=0.448$) between the time spent in each run throughout the entire protocol. For the whole-group, no significant differences ($p\geq 0.05$) were found between 1st run – 12th run in the kinematic variables analysed (Table 1). Significant correlations between the average running pace and $\Delta\theta$hip at toe-off ($R= -0.506$, $p=0.007$) and $\Delta\theta$knee at toe-off ($R= 0.534$, $p=0.004$) were found. Likewise, ΔT400m significantly correlated ($p<0.05$) with changes in ΔSL ($R= -0.568$), and in joint variables ($\Delta\theta$hip and $\Delta\theta$ankle at initial contact, $R= 0.584$ and $R= 0.389$, and $\Delta\theta$hip at midstance, $R= 0.439$).

TABLE 1 ABOUT HERE

The cluster analysis performed according to the average running pace leads to a distinction between faster (pace: 20.8 $km.h^{-1}$, n=15), and slower (pace: 18.01 $km.h^{-1}$, n=13), with no significant differences ($p\geq0.05$) regarding fatigue-related parameters. Another cluster analysis matched the athletes according to the exhaustion level reached during the protocol, into more exhausted (NEG, n=12 - HRpeak: 188 bpm, HRrec: 163 bpm, BLa: 14 mmol.l-1; RPE: 18.7; ΔT400m: -1.44 s), and less exhausted (EG, n=16 - HRpeak: 173 bpm, HRrec: 143 bpm, BLa: 12.9 mmol.l-1; RPE: 18; ΔT400m: 0.82 s) with no significant differences in the average pace ($p=0.270$) (Table 2).

TABLE 2 ABOUT HERE

Spatial-temporal parameters – SL, CT and FT – are shown in Figure 2. No significant differences ($p \geq 0.05$) between groups were found at baseline values (1st run) in any variable, apart from SL ($p=0.029$) between faster (1.92 m) and slower (1.77 m). As for the changes induced during the HIIT, a significant difference ($p=0.048$) was found in ΔCT (+0.011 s in EG and -0.015 s in NEG), whilst the rest of variables did not show significant differences.

FIGURE 2 ABOUT HERE

Table 3 shows the changes induced by the HIIT protocol at kinematic level for faster and slower athletes, and the between-groups comparison. At 1st run, θKnee during the midstance and θKnee and θAnkle during toe-off, were significantly higher in the slower group ($p=0.046$, 0.031 and 0.044, respectively). The between-group difference in θKnee during the midstance was maintained at 12th run ($p=0.004$). As for the changes induced by the running protocol (Δ) no significant differences ($p \geq 0.05$) were found between groups at initial contact or at midstance phases during support, nor during swing. Significant differences were found at toe-off in θHip – faster showing a -1.2º reduction, while slower a 3.8º increase, and θKnee – faster runners increase by 3.5º and the slower ones reduced by -1.6º.

TABLE 3 ABOUT HERE

As for the EG-NEG comparison (Table 4), no significant differences were found at pre-test ($p \geq 0.05$), while at post-test the θAnkle was significantly greater in EG ($p=0.040$). Concerning the within-group comparison, a significant increase ($p<0.05$) was found in θHip during toe-off (+4.3º) for NEG, while a significant impairment was found for NEG during swing in θKnee at toe-off (-5.2º). The average running pace for both groups was similar ($p=0.370$).

TABLE 4 ABOUT HERE

Regarding the FSP (Figure 3), no significant changes were found either for the whole-group ($p=0.199$), or for the created groups (faster, $p=0.368$; slower, $p=0.392$; EG, $p=0.406$; and NEG, $p=0.317$). However, a trend to land with foot zones closer to the heel than forefoot can be observed (-14.2% in forefoot) at the end of the HIIT protocol, although the reduction is minor in both faster and NEG (-6.2% and -9.1%, respectively) than in slower and EG (-23.1% and -17.6%).

FIGURE 3 ABOUT HERE

DISCUSSION

The goal of this study was to determine whether running kinematic characteristics change over a typical HIIT in endurance runners. We hypothesised that certain running kinematic parameters would change between the first and the last runs. The results obtained show that despite the high-level of exhaustion reached by the athletes (HRpeak: 182.3 bpm; HRrec: 155.5 bpm; BLa: 13.7 $\text{mmol}\cdot\text{l}^{-1}$; RPE: 18.3), they were able to maintain a constant running pace throughout the HIIT protocol, and no significant changes were found at kinematic level. This finding is consistent with some previous studies that did not report alterations in running kinematic after different running exercises (1,11,23). However, not all studies on this topic are in agreement and other works have found fatigue-induced changes during running at kinematic level (13,14,22,28,35). As indicated by Kellis and Liassou (27), fatigue has been hypothesised to alter biomechanical and neuromuscular function in a manner that could possibly lead to an increased risk of sustaining musculoskeletal injury, and/or impaired performance. Exercising in a fatigued state has been shown to increase stress, strain, shear, and impact forces within the lower extremity (13,35). Fatigue can have considerable influence on lower extremity mechanics and, with altered neuromuscular function, a reduction in the transfer of mechanical energy between eccentric and concentric muscle contractions can occur along with slower muscle reaction times (35).

The effect of exertion on running kinematics during typical running sessions have been described in the literature, although the information on this topic is not abundant. Analysis of peak joint angles revealed increases in trunk flexion (4º), decreases in trunk extension (3º), and increases in non-dominant ankle eversion (1.6º) (28). Likewise, the data obtained by Mizrahi (35) after 30 min continuous running at anaerobic threshold indicated an increase in knee angle at maximal knee extension, and a decrease in knee flexion angle at foot strike. Focusing on spatial-temporal parameters, some studies (22,35) have reported changes after continuous runs - increased SL with a corresponding decrease in cadence, and decreases in CT occurred in conjunction with increases in FT. As we indicated earlier, the protocols used in these studies are different so that results are quite difficult to compare and consensus has not been reached yet. Considering the whole-group of athletes, the current study shows that this HIIT protocol did not consistently perturb the running kinematics of trained male runners. To the best of the authors' knowledge, just one study has analysed the running kinematic during interval training (11) and, even though the running protocol and the controlled variables are not exactly the same, the main finding is in line with our study.

With concern to the athletic performance, two clusters of endurance athletes were obtained from the different average running pace during the HIIT protocol (Faster vs. Slower). The influence of speed on running kinematics is well documented (7,9,10,31). This study is consistent with those previous works and some differences between faster and slower runners were found at first run (un-fatigued condition) – longer steps for faster runners, and greater θKnee during the midstance and θKnee and θAnkle during toe-off for the slower runners. It is also worth noting that fatigue-induced changes in kinematic response were different between faster and slower. Whereas faster runners reduce θHip (-1.2º) and increase θKnee (+3.5º) at toe-off, slower runners suffer the opposite adaptations (+3.8º and -1.6º respectively). These results partially support the conclusion reported by previous studies (13,27). Those works informed about an increase in hip extension and knee flexion angles at toe-off following an exhausting run, which agrees with the data obtained in this study for the slower runners.

With regard to the influence of the exhaustion level reached on running kinematic during this HIIT protocol, some findings are worthy of discussion. Both EG and NEG are homogenous with regard to the athletic level (similar average running pace during the HIIT) and, while any between-groups difference at kinematic level was found at first run, some differences have been found in fatigue-induced changes at last run. The data obtained show that NEG did not increase CT, (while EG increased it by 0.011 s), as well as increased θHip at toe-off (+4.3º), and experienced a reduction of 5.2º in θknee during swing. The maintenance of CT for NEG is an important finding since is considered an influencing factor in leg stiffness (36). In the presence of fatigue, runners fail to fully utilise the stretch-shortening mechanism (13) and reduce leg stiffness (15), and both factor have exhibited strong correlations with running economy and, consequently, running performance (13,15). Moreover, an increased peak knee flexion during swing supports the ease of the swing phase by increasing angular velocity, and appears to be a more economical running attribute (24). Taken together, although some differences between groups have been found, neither athletic performance nor exhaustion level reached seems to be determinant in the kinematic response during a HIIT, at least for this group of moderately-trained endurance runners.

Finally, another variable examined in this study was the FSP which we have not yet discussed. First, it is worth noting that the reliability obtained in this study is considered as ‘very good’ (29). The effect of FSP on the economy, performance and injury rates in endurance runners has been documented in recent literature (12,31). From the perspective of injury, it has been suggested, on the one hand, that the risk of injury can be diminished by reducing the magnitude of impact forces, which can be achieved by adopting midfoot or forefoot strikes (12). On the other hand, compared to rearfoot, forefoot strikes cause higher joint moments in the ankle, although lower in the knee and hip, which may cause repetitive stress damage in non-skeletal connective tissues that stabilize joints and thus, it might increase the risk of Achilles tendinopathies, injuries of the foot, and stress fractures of the metatarsals (12). Whilst it is not known if higher joint moments cause injuries, it is clear that the most important difference between rearfoot and forefoot strike, from the perspective of injury, is the nature of the impact peak at the initial contact (12).

It has been established that the pattern of the FSP depends to some extent on the speed, running surface, footwear and fatigue (12). The current study focused on fatigue-induced changes by a typical HIIT for endurance runners and, to the best of the authors’ knowledge, this is the first study to do this, with previous papers examining FSP during long-distance road competition (30,31). In accord with those studies, this work shows that in presence of fatigue, FSP tends to change by diminishing the frequencies of forefoot and increasing midfoot and rearfoot strikes – although substantial changes were not found. From EG vs. NEG comparison, we obtain evidence to support the idea that fatigue is an influence factor in FSP with EG reducing the frequency of forefoot (-17.6%) more than NEG (-9.1%) at the end of HIIT.

Three-dimensional motion analysis has been the ‘gold standard’ in kinematic analysis and the authors are aware that it is the main limitation of this study. However, the three-dimensional (3D) method relies on multiple expensive cameras and time-intensive setup procedures whilst two-dimensional motion analysis relies on fewer cameras than 3D, which reduces cost and setup time. Hence, notwithstanding these limitations, the current field-based study offers some insight into the impact of a common HIIT at kinematic level in endurance runners.

This study has shown that a common HIIT session for endurance runners, consisting of 3x4x400 m repeats, did not consistently or substantially perturb the running kinematics of trained male runners. Additionally, although some differences between groups have been found, neither athletic performance nor exhaustion level reached seems to be determinant in the kinematic response during a HIIT, at least for this group of moderately-trained endurance runners.

Practical Applications

In general, the practical implications of these findings are that coaches and runners need not fear substantial detrimental effects from HIITs on running technique. Such information is essential for the design of more effective training programmes for injury prevention and performance enhancement in running. Knowledge about the effect of every training session on the athlete plays a key role in proper training prescription, which means that a further description of the impact of the most typical running exercises on endurance runners is needed, which can lead to better understanding and accuracy in the training prescription process. Additionally, since most injuries in running can be attributed to overuse from repeated bouts of activity, more evidence is needed about the cumulative effects of HIIT-based running sessions.

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Table 1. Means (±SD) of kinematic variables during the first and last run of a high-intensity intermittent training.

	1st run	12th run	Δ (%)	*p-value*
Initial contact				
θHip (º)	147.8 ± 5.53	146.51 ± 5.76	-1.29 (0.87)	0.244
θKnee (º)	155.79 ± 7.26	155.72 ± 5.65	-0.07 (0.04)	0.955
θAnkle (º)	105.51 ± 9.14	104.25 ± 7.37	-1.26 (1.19)	0.500
Midstance				
θHip (º)	152.87 ± 6.69	154.33 ± 6.54	1.46 (0.96)	0.274
θKnee (º)	135.32 ± 5.76	135.43 ± 4.99	0.11 (0.08)	0.905
θAnkle (º)	85.29 ± 5.69	85.35 ± 7.75	0.06 (0.07)	0.970
Toe-off				
θHip (º)	167.27 ± 5.53	168.49 ± 6.45	1.22 (0.73)	0.348
θKnee (º)	163.94 ± 6.1	163.11 ± 5.15	-0.83 (0.51)	0.410
θAnkle (º)	124.74 ± 10.49	129.35 ± 10.2	4.61 (3.71)	0.079
Swing				
θKnee at initial contact (º)	83.39 ± 22.49	80.72 ± 14.3	-2.67 (3.20)	0.533
θKnee at midstance (º)	47.94 ± 9.05	48.47 ± 8.87	0.53 (1.11)	0.735
θHip at toe-off (º)	129.63 ± 6.7	127.06 ± 7.2	-2.57 (1.99)	0.086
θKnee at toe-off (º)	93.22 ± 10.3	89.69 ± 11.5	-3.53 (3.79)	0.066

Δ: increase, 12th – 1st run; θ: joint angle

Table 2. Parameters related to exhaustion level reached during the HIIT (Mean ± SD) for the whole-group (n=28) and for the groups created according to average running pace (Faster and Slower) and exhaustion level reached during the protocol (exhausted and non-exhausted groups, EG and NEG respectively).

Variables	Whole-group	Faster	Slower	$F_{(1-27)}$	*p-value*	EG	NEG	$F_{(1-27)}$	*p-value*
Physiological measures									
HRpeak (bpm)	182.27 ± 9.8	183.64±9.3	180.89±10.5	0.558	0.462	188.04±5.4	173.87±8.7	27.230	<0.001
HRrec (bpm)	155.54 ± 13	157.65±12.3	153.26±14.0	0.747	0.396	163.8±9.22	143.57±7.44	36.36	<0.001
BLa (mmol·l^{-1})	13.68 ± 2.38	13.39±2.46	13.98±2.33	0.407	0.529	14.16±2.3	12.9±2.39	1.670	0.047
RPE (6-20)	18.34 ± 1.01	18.41±0.78	18.27±1.25	0.137	0.714	18.7±0.8	18.0±1.16	3.206	0.085
Athletic performance									
Running pace (km.h^{-1})	19.22 ± 1.38	20.84±0.82	18.05±0.83	48.79	<0.001	19.44±1.36	18.9±1.4	1.270	0.270
ΔT400m (s)	-0.86 ± 5.75	-0.2±5.63	-1.62±6.00	0.412	0.527	-1.44±5.32	0.82±5.93	1.069	0.311

HRpeak: peak heart rate; HRrec: recovery heart rate at 1 min post-exercise; BLa: blood lactate accumulation; RPE: rate of perceived exertion on a 6-20 scale; ΔT400m: the impairment in the time spent (12th run – 1st run).

Table 3. Means (±SD) of kinematic variables during the first and last run of a high-intensity intermittent training for the created groups (Faster and Slower) according to their average running pace during the protocol

Variables	1st run		$F_{(1\text{-}26)}$	*p-value*	12th run		$F_{(1\text{-}26)}$	p-value	Δ		$F_{(1\text{-}26)}$	*p-value*
	Faster	Slower			Faster	Slower			Faster	Slower		
Initial contact												
θHip (º)	146.1±5.4	149.3±5.4	2.390	0.134	145.4±6.3	147.8±5.1	1.184	0.287	-1.1±6.1	-1.6±5.4	0.044	0.836
θKnee (º)	154.4±6.3	157.9±7.9	1.680	0.206	154.6±5.2	156.9±6.1	1.113	0.302	0.8±5.8	-0.9±6.5	0.518	0.478
θAnkle (º)	104.2±6.3	106.8±11.5	0.574	0.455	105.4±8.4	103.0±6.1	0.712	0.407	1.1±6.2	-3.8±12.1	1.767	0.196
Midstance												
θHip (º)	152.1±6.5	153.2±7.1	0.188	0.668	154.3±7.4	154.4±5.7	0.003	0.958	1.2±6.5	1.7±7.3	0.041	0.841
θKnee (º)	133.6±4.7	137.4±6.1	3.423	0.046	132.9±3.9	138.2±4.7	10.111	0.004	0.8±4.3	-0.5±5.6	0.425	0.520
θAnkle (º)	86.8±4.9	86.5±6.7	0.596	0.447	83.2±5.2	87.7±9.5	2.432	0.131	1.2±10.9	-1.1±4.1	0.515	0.480
Toe-off												
θHip (º)	168.6±5.2	166.1±5.7	1.522	0.228	167.2±5.7	169.9±7.2	1.162	0.291	3.8±5.6	-1.2±6.7^	4.476	0.044
θKnee (º)	161.7±5.3	166.5±5.9	5.196	0.031	163.1±4.9	163.1±5.6	0.001	0.989	-3.5±5.1	1.6±4.2^	8.020	0.009
θAnkle (º)	121.4±12.2	129.3±5.9	4.500	0.044	127.8±8.7	131.1±11.7	0.651	0.427	1.8±13.4^	7.3±12.6	1.274	0.270
Swing												
θKnee at initial contact (º)	78.9±12.5	80.2±14.9	0.061	0.807	77.7±13.5	84.1±14.9	1.344	0.257	3.8±13.8	-8.7±26.6	2.301	0.142
θKnee at midstance (º)	44.9±9.6	50.2±8.4	2.287	0.143	46.8±8.6	50.2±9.2	0.983	0.331	0.1±4.5	1.0±10.5	0.096	0.760
θHip at toe-off (º)	128.5±7.6	130.9±5.2	0.874	0.358	125.5±7.9	128.8±6.2	1.407	0.247	-2.1±5.7	-2.9±9.0	0.089	0.767
θKnee at toe-off (º)	88.8±13.5	96.6±10.9	2.729	0.111	88.9±13.5	90.5±14.1	0.086	0.772	-6.1±9.8	-1.2±9.1^	1.821	0.189

^indicates within-group (1st run vs. 12th run) significant differences $p<0.05$; Δ: increase, 12th run - 1st run; θ: joint angle

Table 4. Means (±SD) of kinematic variables during the first and last run of a high-intensity intermittent training for the created groups (exhausted and non-exhausted groups) according to the exhaustion level reached during the protocol.

Variables	1st run		$F_{(1-26)}$	*p-value*	12th run		$F_{(1-26)}$	p-value	Δ		$F_{(1-26)}$	*p-value*
	EG	NEG			EG	NEG			EG	NEG		
Initial contact												
θHip (º)	147.0±5.8	148.2±5.5	0.331	0.570	146.5±5.3	146.7±6.7	0.006	0.938	-0.7±5.8	-1.5±5.7	0.111	0.742
θKnee (º)	155.2±6.7	156.9±8.4	0.357	0.555	155.9±5.2	156.1±6.3	0.001	0.972	1.2±5.7	-0.9±6.4	0.765	0.391
θAnkle (º)	106.5±10.4	103.7±7.1	0.587	0.451	104.7±7.4	104.1±7.7	0.041	0.842	-2.1±11.4	0.4±7.3	0.396	0.535
Midstance												
θHip (º)	151.9±6.8	153.2±6.8	0.258	0.616	154.4±6.6	154.6±6.9	0.007	0.935	2.2±6.8	1.4±6.7	0.078	0.783
θKnee (º)	134.2±6.0	136.2±4.6	0.820	0.374	135.6±5.5	135.8±4.3	0.016	0.901	1.5±4.4	-0.3±3.1	1.424	0.244
θAnkle (º)	85.4±4.9	86.3±7.1	0.160	0.693	87.5±9.2	82.8±4.7	2.333	0.040	2.6±8.8	-3.5±6.1	3.888	0.060
Toe-off												
θHip (º)	168.6±5.0	165.9±6.1	1.478	0.235	167.8±6.1	170.3±6.5	0.956	0.338	-0.6±6.7	4.3±5.5^	3.902	0.060
θKnee (º)	162.9±7.0	165.5±4.2	1.224	0.279	162.5±5.5	163.5±4.8	0.221	0.643	-0.2±6.2	-2.0±3.5	0.703	0.410
θAnkle (º)	124.1±11.8	125.7±8.6	0.152	0.700	128.7±10.1	129.2±10.7	0.015	0.904	5.4±14.5	3.5±12.2	0.151	0.737
Swing												
θKnee at initial contact (º)	74.9±11.2	84.1±14.7	3.304	0.082	78.3±12.2	85.3±14.4	1.570	0.222	-3.6±15.1	1.1±14.5	0.299	0.589
θKnee at midstance (º)	44.6±9.1	50.5±8.5	2.874	0.102	47.3±7.7	50.2±10.8	0.633	0.434	2.0±7.9	-0.3±7.8	0.525	0.476
θHip at toe-off (º)	127.9±6.5	131.6±6.3	2.116	0.158	127.1±5.4	126.4±9.4	0.061	0.807	-0.8±6.1	-5.3±8.9	2.345	0.139
θKnee at toe-off (º)	91.3±14.6	93.9±10.8	0.261	0.614	90.4±13.9	88.8±14.3	0.084	0.774	-2.3±11.3	-5.2±7.4^	0.542	0.469

^indicates within-group (1st run vs. 12th run) significant differences $p<0.05$; Δ: increase, 12th run - 1st run; θ: joint angle; EG: exhausted group; NEG: non-exhausted group

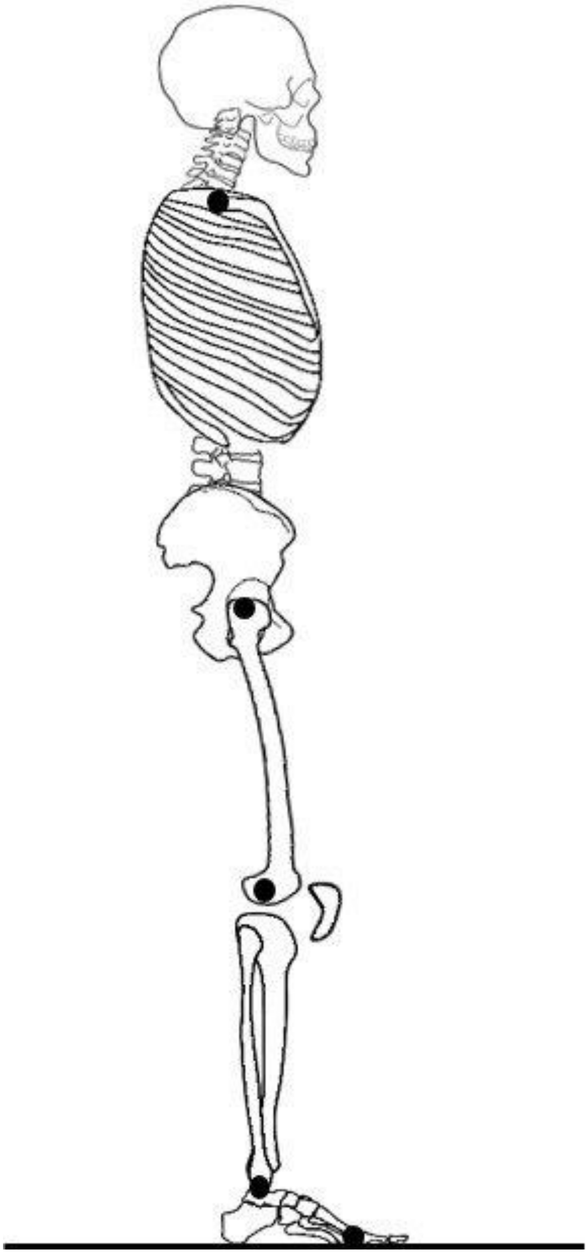

Figure 1. Landmarks placement. 1: acromion; 2: greater trochanter; 3: lateral epicondyle of the femur; 4: lateral malleolus; 5: fifth metatarsal

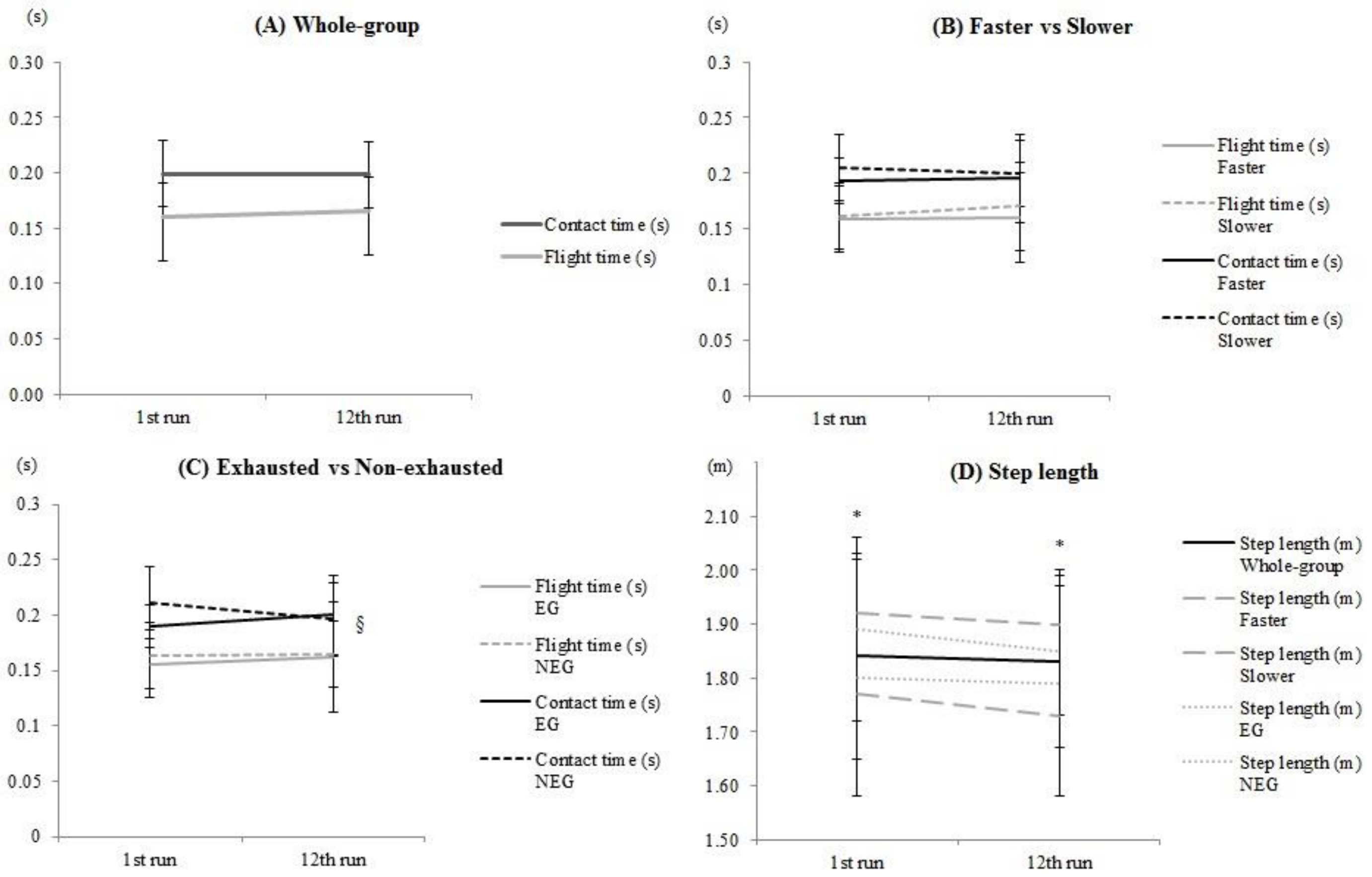

Figure 2. Spatial-temporal parameters during a high-intensity intermittent running (1st run – 12th run) for the whole-group, and groups created according to average running pace (Faster vs. Slower) and exhaustion level reached (EG vs. NEG – exhausted and non-exhausted group, respectively). (A) Contact time and flight for the whole-group; (B) Contact time and flight for the Faster vs. Slower; (C) Contact time and flight for EG vs. NEG; (D) Step length for the whole-group and created groups. * indicates significant differences between-groups either at first or at last run ($p<0.05$); § indicates significant differences ($p<0.05$) between-groups in the fatigue-induced changes (Δ)

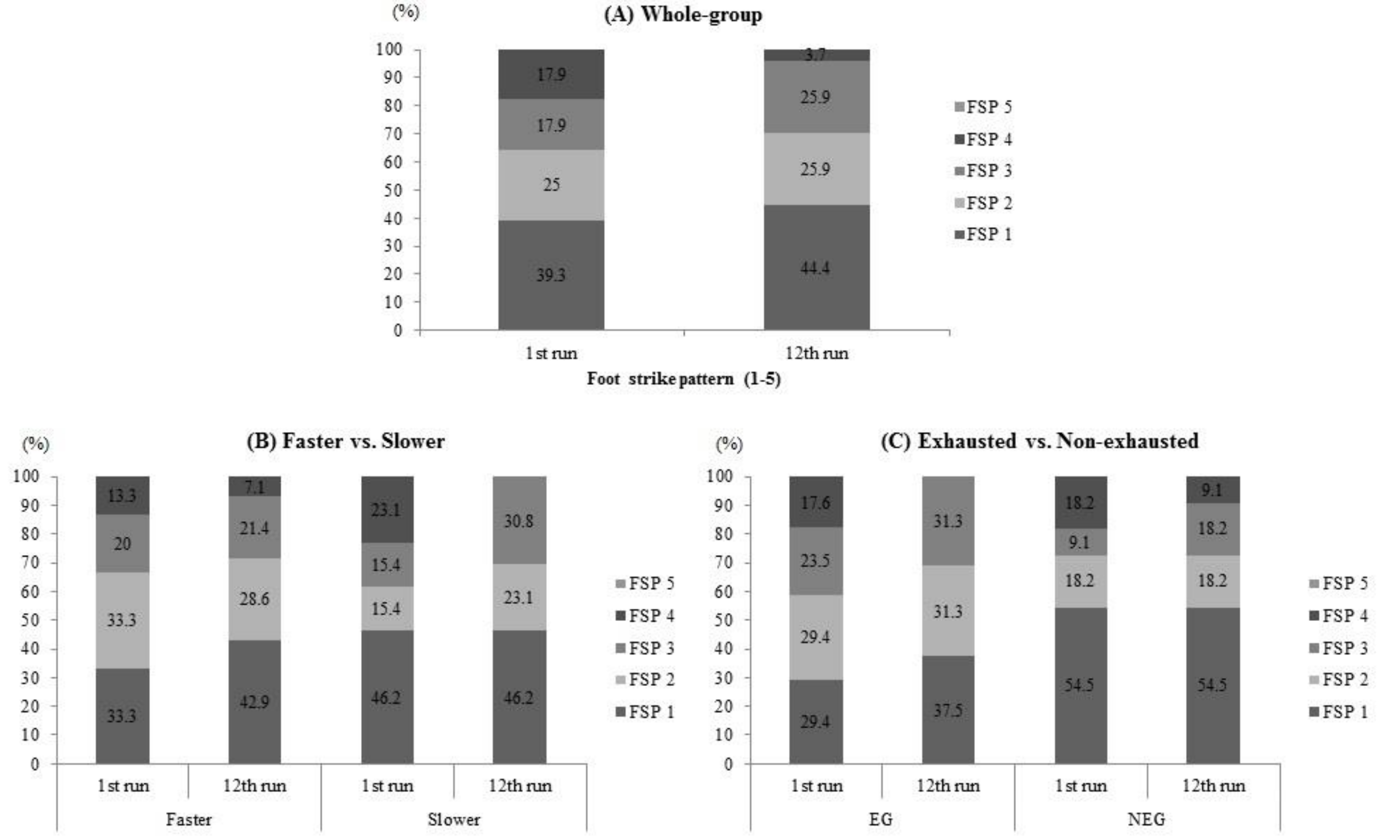

Figure 3. Foot strike pattern (FSP) and changes induced over a high-intensity intermittent running for the whole-group (A), and for created groups: (B) according to average running pace – Faster vs. Slower, and (C) to exhaustion level reached – exhausted and non-exhausted group (EG vs. NEG, respectively). FSP1: high-rearfoot strike; FSP2: rearfoot strike; FSP3: midfoot; FSP4: forefoot strike; FSP5: high-forefoot strike

3. HIGH-INTENSITY INTERMITTENT TRAINING PRESCRIPTION FOR ENDURANCE RUNNERS: IS A FEW LONG RUNS MORE EFFECTIVE THAN A HIGHER NUMBER OF SHORTER RUNS?

(PAPERS V, VI AND VII)

Acute metabolic, physiological and neuromuscular responses to two high-intensity intermittent training protocols in endurance runners

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Acute metabolic, physiological and neuromuscular responses to two high-intensity intermittent training protocols in endurance runners

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Abstract.
BACKGROUND: Since a growing body of evidence points to mean training intensity over a season as a key factor to performance improvements, and there is wide evidence of the benefits of high-intensity intermittent training (HIIT) for endurance athletes, coaches need further information about the acute impact of typical HIIT workouts on endurance runners.
OBJECTIVE: To compare the physiological strain and muscular performance parameters of endurance runners during two HIIT workouts by determining whether a typical HIIT for endurance runners (10 × 400 m) leads to a similar impact as a HIIT protocol (40 × 100 m) that increases the average training pace despite maintaining the same training volume.
METHODS: Eighteen endurance runners performed 2 HIITs. Metabolic (blood lactate [BLa], blood ammonia [BAmm]), neuromuscular (countermovement jump [CMJ], handgrip strength test [HS]), and physiological responses were monitored during both protocols.
RESULTS: No significant differences between HIITs were found for BLa_1 min post-test, BAmm, HS and HRpeak. Significant differences were found in fatigue-induced changes in CMJ performance (-0.36 cm in 40 × 100 m; $+1.48$ cm in 10 × 400 m), and in average pace ($P < 0.001$) which was faster during the 40 × 100 m.
CONCLUSIONS: Despite similar physiological, metabolic, and HS responses, the 40 × 100 m protocol allowed runners to train at a higher intensity, which might have important effects on the training prescription for endurance runners.

Keywords: Blood metabolites, mechanical power, endurance athletes, physiological strain

1. Introduction

High-intensity intermittent training (HIIT) involves repeated bouts of high-intensity exercise interspersed with recovery periods. It has been used by athletes for almost a century now, and is today considered one of the most effective forms of exercise for improving the physical performance of athletes [1,2]. Nevertheless,

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the available information about the acute physiological impact of typical HIITs on endurance runners is scarce. To the best of our knowledge, only one previous study [3] has specifically focused on this topic. A description of the metabolic and neuromuscular responses to the training sessions of endurance runners may lead to a better understanding of the factors that limit performance, and this will help in the preparation of a scientifically-based and well-balanced training programme for improving running performance.

Coaches have questioned whether it would be more effective to perform a higher number of shorter runs, or a few long runs during a HIIT workout. It seems clear that changes in the length of efforts and recovery intervals during HIITs (training load in terms of intensity, volume and density) will challenge both the metabolic and the neuromuscular systems at different levels [1–3]. Vuorimaa et al. [3] compared the physiological strain and muscular performance of athletes during two HIIT workouts at velocities associated with maximal oxygen uptake (VO_{2max}): 14 runs of 60 seconds separated by 60 seconds of rest and 7 runs of 120 seconds interspersed with 120 seconds of rest; however, both protocols had a different physiological response. Thus, the key point for coaches and athletes is whether at the same absolute training load/volume it is possible to increase the average training pace, by modifying other variables such as intensity or the number of runs, without changing the physiological and neuromuscular impact.

Taking the above question into account, the main goal of this study was to compare the physiological strain and muscular performance parameters of endurance runners during two HIIT workouts in order to determine whether splitting HIIT workouts done by endurance runners, such as whether 10 runs of 400 metres (10 × 400 m) and 40 runs of 100 metres (40 × 100 m), leads to similar metabolic and muscle power output changes. The authors hypothesized that, despite keeping the same training volume, a greater number of shorter running bouts would increase the average training pace with the same physiological strain and neuromuscular effects.

2. Methods

A crossover study design was used to compare physiological and neuromuscular performance parameters from two HIIT workouts done by endurance runners. A further description of the response to different training sessions of endurance runners may lead to a better understanding of the factors that limit performance, and this will help coaches in their training prescriptions. Additionally, by comparing the acute response to these different HIIT workouts, this study tries to highlight whether, at the same training volume, it is possible to increase the average training pace, by modifying other variables such as intensity or the number of runs, without changing the physiological and neuromuscular impact. This would provide useful information for athletes and coaches in the preparation of a scientifically-based and well-balanced training program for improving athletic performance.

2.1. Subjects

A group of eighteen recreationally trained endurance runners (mean ± SD, age = 30.89 ± 11.69 years; body mass index [BMI] = 22.08 ± 2.17 kg/m^2; 16 males and 2 females) voluntarily participated in this study. No general clinical examination was carried out, but all subjects were medically examined annually. The subjects had trained for 1–3 hours a day, 4–6 days a week all year round for a minimum of four years and had no history of an injury in their three months before they participated. The study was conducted in November 2014 during the cross-country season and the competition phase of their yearly program, at a time when most of the athletes were at a high level of competitive fitness. At the time of these observations, the track athletes had completed between two and four months of training for that season. More information about the participants is presented in Table 1.

After receiving detailed information on the objectives and procedures for the study, each subject signed an informed consent form to participate, which complied with the ethical standards of the World Medical Association's Declaration of Helsinki (2008) and made clear that they were free to leave the study if they saw fit. The study was approved by the Ethics Committee of the University of Jaen (Spain).

2.2. Procedures

The participants were asked not to engage in any high intensity exercise during the 72 hours before the experiment and to have a meal at least two hours before the beginning of warm up. All athletes had experience with the exercises to be analysed. All the training sessions were carried out between 17:00 and 21:00 hours on an outdoor 400-m synthetic track. Before the

Table 1
Anthropometric characteristics and training background of participants (mean ± SD, $n = 18$)

Age (years)	Body mass (kg)	Height (m)	BMI (kg/m^2)	Training experience (years)	VVO$_{2max}$ (km.h^{-1})
30.89 ±11.69	65.78 ± 9.02	1.72 ± 0.06	22.08 ± 2.17	7.00 ± 2.61	17.24 ± 1.37

BMI: body mass index; VVO$_{2max}$: velocity associated to maximal oxygen uptake.

running exercises, the athletes performed a warm up, which consisted of ten minutes of continuous running and ten minutes of general exercises (high skipping, leg flexion, jumping exercises, short bursts of acceleration).

Each athlete was tested on two occasions, separated by seven days: (1) ten runs of 400 m with 90–120 s of recovery between running bouts (10 × 400 m); (2) 40 runs of 100 m with 25–30 s of recovery between runs (40 × 100 m). Both running exercises show the same volume (4000 m), similar percentage of total training time in which athlete is working (39.5% and 40.7% respectively) and Work:Rest ratio -coefficient between work period and rest period- (0.65 and 0.67 respectively). In order to avoid "an order effect" the protocol was counterbalanced. Both HIIT protocols were carried out above the velocity associated with VO$_{2max}$(VV$_{O2max}$), which was indirectly measured from the velocity of a 3000 m race [4]. A passive recovery between runs was undertaken during both HIIT protocols, as they stood upright. Participants are experienced athletes who performed these types of workouts in their training program so, the only instructions were to finish the protocols as fast as they could as they maintained a constant speed to the best of their ability. No more guidelines were provided as to exercise intensity, though subjects were informed to run at a self-selected exercise intensity. Metabolic, physiological and neuromuscular responses were monitored during both running protocols. The performance of every single run was also recorded through time spent (T400 m and T100 m, respectively, in seconds). An illustration of both HIIT protocols (10 × 400 m and 40 × 100 m) based on heart rate response is presented in Fig. 1.

2.3. Materials and testing

2.3.1. Anthropometric variables

Height (m) and body mass (kg) were measured at the start of the first test session, whilst body mass index (BMI) was calculated by means of the following equation: body mass (kg)/height (m^2). A stadiometer (Seca 222, Hamburg, Germany) and a calibrated bascule (Seca 634, Hamburg, Germany) were used for that purpose.

2.3.2. Metabolic variables

Blood lactate (BLa) and blood ammonia (BAmm) were recorded during the recovery period after the last run of each training protocol (BLa at 1 min and 5 min post-test; BAmm at 1 min post-test). For this purpose, fingertip blood samples were analysed through a portable lactate analyser (Scout Lactate, SensLab GmbH, Leipzig, Germany) and a portable ammonia analyser (PocketChem Ba Pa-4130, Menarini DIAGNOSTICS, Florence, Italy). Both lactate and ammonia analysers were checked for accuracy according to the manufacturer's instructions before every testing session. The difference between the accumulated BLa at 1 min and at 5 min post-testing is termed 'BLa clearance' [5].

2.3.3. Physiological variables

Cardiovascular responses were monitored (Garmin Forerunner 405, KS, USA) throughout the 10 × 400 m and 40 × 100 m protocols. Peak (HRpeak) and average heart rates (HRmean), as well as at the end of recovery (heart rate recovery, HRrec) were recorded during both running protocols. As indicated by Daanen et al. [6], although HRrec is generally expressed in absolute terms (bpm), it can be useful to express it relative to the HRrec (i.e. the difference between resting and maximal heart rate) to minimize interpersonal differences. Based on this, the difference between HRpeak and HRrec was calculated and was called the heart rate reserve (HRR, in bpm). Because the rest periods of both HIIT protocols were different, comparing the absolute values of the HRrec and HRR would not be correct. Thus, in an attempt to control the impairment of cardiac recovery capacity throughout both running protocols, the difference between the first and the last run (increase, Δ) was used for the statistical analysis. Moreover, in order to obtain further information about the perceived exertion, the rate of perceived exertion (RPE) was recorded on the 6–20 Borg Scale [7] immediately after the last run in both protocols.

2.3.4. Neuromuscular variables

Countermovement vertical jump (CMJ) and handgrip strength tests were performed before (pre-test, unfatigued condition) and immediately after each running

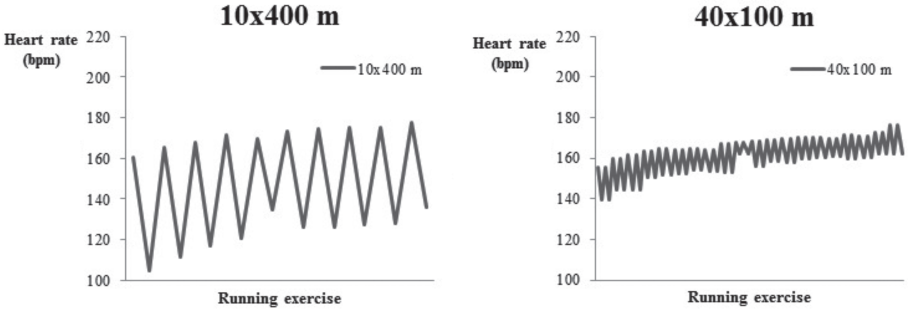

Fig. 1. An example from one athlete: Illustration of both HIIT protocols (10 × 400 m and 40 × 100 m), based on heart rate response (bpm).

workout (post-test, fatigued condition). The participants were experienced athletes who performed CMJ in their daily training sessions. Moreover, to make sure the execution of the CMJ was correct, a familiarization session was carried out beforehand. The CMJ was recorded using the OptoGait system (Microgate, Bolzano, Italy), which was also used in a similar study [8]. This device measures the contact time on the floor and the flight time using photoelectric cells. Flight time was used to calculate the height of the rise using the body's center of gravity. Subjects performed three trials with a 15-second recovery period between them, and the best trial was used for the statistical analysis. The handgrip strength test (HS) was performed as recommended by a previous study [9]. To record the HS (in kilograms), a digital hand dynamometer was used (TKK 5101 Grip D, Takey, Tokyo, Japan). The optimum grip was adjusted with the calibration formula of Ruiz et al. [9]. Two attempts at HS were performed with each hand, lasting 3 seconds each, and separated by 15 seconds of recovery. The best trial was used for analysis. In both tests (CMJ and HS) the post and pre-test differences (increase, Δ) were also calculated and used for the subsequent analysis. Participants were verbally encouraged to achieve maximum performance throughout both running protocols.

2.4. *Statistical analysis*

Descriptive statistics are represented as means (SD). Tests for normality and homogeneity of variances (Shapiro-Wilk and Levene's) were conducted on all data before analysis. The comparative analysis between both HIIT protocols (10 × 400 m and 40 × 100 m) for each variable analyzed (heart rate response, perceived exertion, average running pace, metabolic response, and neuromuscular response in both pre- and post-test) was performed by Student's t-test for paired samples. Analysis of variance (ANOVA) was performed for running pace throughout both HIIT workouts (within protocol, to determine if changes in pace were found during both protocols). The level of significance was $P < 0.05$. Data analysis was performed using SPSS (version 21, SPSS Inc., Chicago, IL).

3. Results

Heart rate response, RPE and average running pace in both exercises are presented in Table 2. No significant differences among running protocols were found for HRpeak, whilst the HRmean was significantly higher ($P < 0.001$) in the 40 × 100 m. No significant differences between HIITs were found in either the ΔHRrec or the ΔHRR ($P = 0.091$ and $P = 0.067$, respectively). Significant differences between both HIITs were found for RPE ($P = 0.019$), with lower values in the 40 × 100 m. Likewise, significant differences ($P < 0.001$) between the HIITs were also found in running pace or %VVO$_{2max}$ ($P < 0.001$) with a faster average pace in the 40 × 100 m. The speed maintained during each HIIT protocol is shown in Fig. 2. No significant differences in 10 × 400 m ($P = 0.089$) or in 40 × 100 m ($P = 0.121$) were found.

The responses to both HIIT workouts for BLa and BAmm levels are shown in Fig. 3. No significant differences ($P = 0.670$) were found in BLa at 1 minute post-exercise, but significantly different values ($P = 0.013$) were found at 5 minutes post-exercise (+2.04 mmol.L^{-1} in 10 × 400 m protocol). As for BAmm, no significant differences were found between both HIIT protocols ($P = 0.611$).

The neuromuscular response to both HIIT protocols, measured by means of CMJ and HS, are presented in Fig. 4. No significant differences were found in HS at pre-test ($P = 0.646$) or at post-test ($P = 0.930$). The CMJ performance between each HIIT was significantly different at pre-test ($P = 0.002$, +1.14 cm in 10

Table 2
Heart rate response, rate of perceived exertion and average running pace during two high-intensity training protocols (10 × 400 m and 40 × 100 m)

Variables	10 × 400 m mean (SD)	40 × 100 m mean (SD)	*p-value*
HRpeak (bpm)	179.00 (9.07)	176.25 (9.64)	0.067
HRmean (bpm)	144.12 (14.29)	160.60 (12.64)	< 0.001
ΔHRrec (bpm)	31.00 (14.09)	22.88 (14.23)	0.091
ΔHRR (bpm)	−13.80 (16.55)	−3.00 (14.36)	0.067
RPE (6–20)	16.00 (1.24)	15.11 (1.13)	0.019
Running pace (km.h^{-1})	18.47 (1.51)$^{\wedge}$	21.60 (1.72)$^{\wedge}$	< 0.001
%VVO$_{2max}$(%)	107.17 (2.83)	125.40 (4.89)	< 0.001

$^{\wedge}$indicates no significant differences intra-running protocols, constant speed; 10 × 400 m: 10 runs of 400-m with 90–120 s of recovery between running bouts; 40 × 100 m: 40 runs of 100-m with 25–30 s of recovery between runs; HRpeak: peak heart rate; HRmean: mean heart rate; ΔHRrec: heart rate recovery in the last run minus HRrec in the first one; ΔHRR: heart rate reserve in the last run minus HRR in the first one; RPE: rate of perceived exertion in a 6–20 scale; %VVO$_{2max}$: percentage of velocity associated to maximal oxygen uptake.

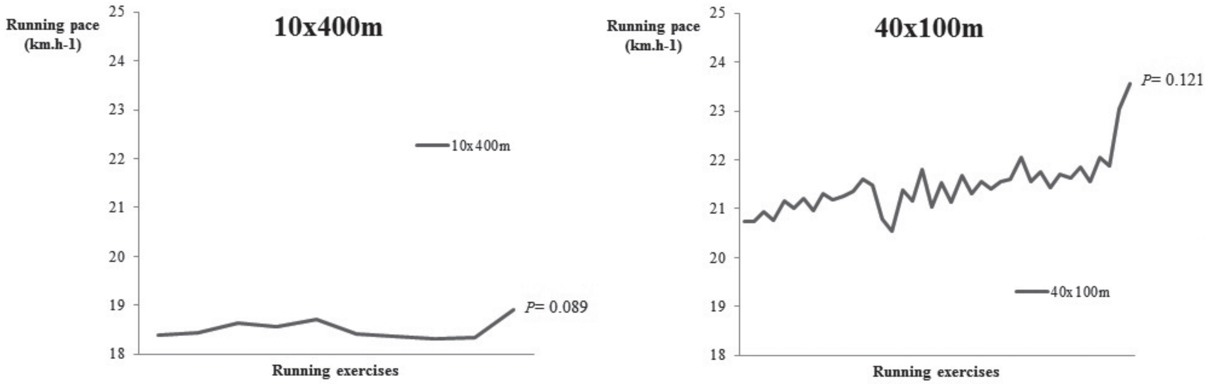

Fig. 2. Running pace (km·h^{-1}) during both high-intensity intermittent training protocols (10 × 400 m and 40 × 100 m).

× 400 m), whilst no significant differences were found at post-test ($P = 0.149$). The post-pre differences between protocols were found to be significant (ΔCMJ; −0.36 cm in 40 × 100 m; +1.48 cm in 10 × 400 m; $P = 0.001$).

4. Discussion

The purpose of this study was to describe the impact of two HIIT protocols with identical volumes of exercise (4000 m) on metabolic, physiological, and neuromuscular levels in order to find out whether shorter but faster running bouts (40 × 100 m) lead to similar metabolic and muscle power output changes as a typical HIIT for endurance runners based on longer and slower runs (10 × 400 m). The results partially confirm the initial hypothesis: BLa and BAmm levels after exercise, the HRpeak reached during exercise, and the heart rate recovery capacity (ΔHRrec and ΔHRR) were similar in both HIIT protocols despite the 40 × 100 m paradigm letting runners train at a higher running pace (+3.13 km.h^{-1}) than the 10 × 400 m. However, the neuromuscular response, which were indirectly measured by means of CMJ and HS performance, showed some differences between the HIIT protocols, there was a non-significant reduction in CMJ after the 40 × 100 m paradigm (−0.36 cm) and an improvement after the 10 × 400 m (+1.48 cm) in relation to baseline values, whilst HS remained unchanged after both HIIT protocols. It is also worth noting athletic performance -in terms of pace- was not impaired during any of HIITs, so athletes were able to maintain regular running speeds during both protocols.

Both metabolic markers and vertical jumping height are of interest because they are considered to indirectly reflect the degree of anaerobic glycolysis activation (BLa) [10], muscle ammonia formation, and muscle ATP depletion (BAmm) [11], as well as the capability of the leg extensor muscles to generate mechanical power (CMJ) [12]. As for the HS test, Millet and Lepers [13] hypothesized that grip strength loss (muscles not involved) after running would be a good indicator of supraspinal fatigue; thus, in line with some authors [13,14], we found it convenient to use this sim-

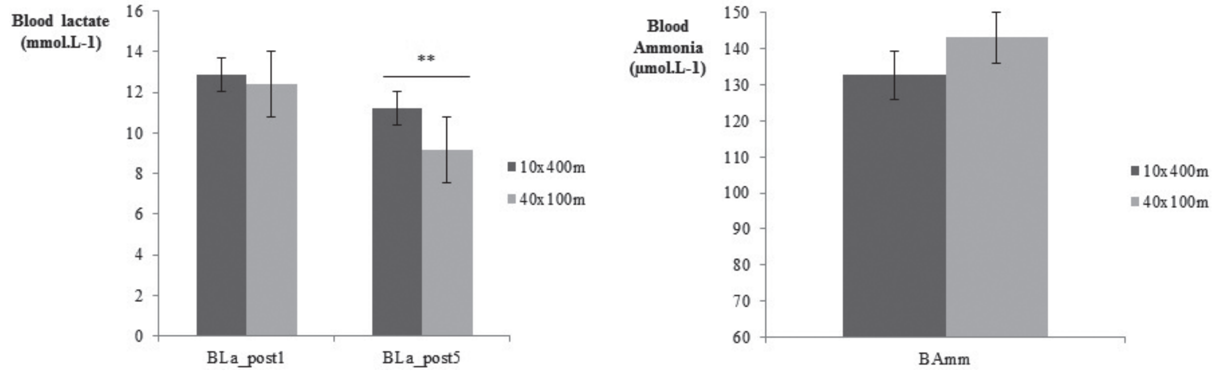

Fig. 3. Metabolic response (BLa and BAmm) to both HIIT protocols (10 × 400 m and 40 × 100 m).

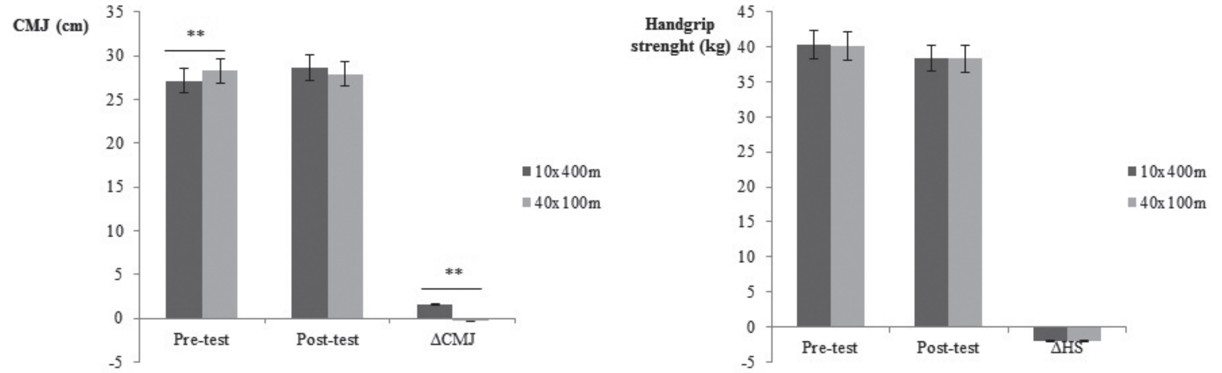

Fig. 4. Neuromuscular response (CMJ and HS) to both HIIT protocols (10 × 400 m and 40 × 100 m).

ple type of measure to explore the possible existence of supraspinal fatigue after endurance exercise.

It is well known that any training stimulus leads to changes in both central and peripheral systems. In the current study, despite that running pace was not impaired during any HIIT, there was a non-significant impairment of CMJ performance after the 40 × 100 m protocol, whilst CMJ performance after the 10 × 400 m paradigm improved, relative to baseline values. This might be due to post-activation potentiation (PAP), which refers to the phenomenon of significantly enhanced muscular twitch force after voluntary contractile activity [15]. In this case, and considering the lack of differences in metabolic markers (BLa and BAmm) during both HIIT protocols, it seems the running pace might be responsible for these muscle power output changes. A faster running pace during the 40 × 100 m protocol (faster average pace and higher %VVO_{2max}) imposes higher demands on neural drive, which leads to a failure to fully activate the contracting musculature [16]. This is mainly because higher intensity training will recruit additional fast twitch motor units for relatively short durations [17], even though these data should be interpreted with caution since baseline values (CMJ performance at pre-test) were different during the first and second testing days. As indicated by Buchheit and Laursen [1], quantifying the neuromuscular load of any training session is important, since it may influence injury risk during (i.e. traumatic-type injuries) and following (i.e. overuse-type injuries both in runners) exercise bouts. On the one hand, increases in running speed lead higher impact forces imposed on the lower limbs [18] and greater levels of neuromuscular engagement [19]. However, some previous studies [20,21] reported that foot strike patterns are at least in part dependent upon running speed so that runners use predominantly a forefoot strike when running faster, which seems to be related with a lower injury risk [21]. Hence, the average running pace in each workout should be considered within the context of both training load and injury management.

In addition, the maintenance of HS performance after both HIITs indicates the importance of central mechanisms to maintain force [13,22]. Central fatigue induced by exercise is manifested by a decrease in muscle activation [22], so the decreased muscular force in those muscles not involved in the exercise will indicate supraspinal fatigue [13]. The results obtained support previous studies [13,14] which also noted the absence of changes in the force of muscles not involved in a prolonged running by measuring HS, and led authors to conclude that selective supraspinal fatigue was not significant in this study. Hence, data obtained from neuromuscular variables (CMJ and HS) support the conclusion reached by Bishop [23], who suggested peripheral mechanisms are the predominant cause of fatigue during HIIT.

Regarding the metabolic response to both HIIT protocols, high values of both BLa (10 × 400 m: 12.87 mmol.L^{-1}; 40 × 100 m: 12.4 mmol.L^{-1}) and BAmm (10 × 400 m: 132.61 μmol.L^{-1}; 40 × 100 m: 143 μmol.L^{-1}) were observed at the end of both HIITs. These high levels of BLa suggest that anaerobic glycogenolysis is extensively activated during these protocols, preferentially in type IIx muscle fibers [24]. There are numerous contrasting views of the physiological effects of lactate and its role post-production. For instance, there is a clear association between the production of lactate and muscular fatigue [25]. High BLa reflects decreased muscle pH and a concomitant fall in muscle force output [4]. However, muscle is also considered to be a consumer of lactate [25]. As indicated by Brooks [26], a relatively high BLa level ($>$ 10 mmol.L^{-1}) may also indicate high lactate consumption in working skeletal muscles, which may in fact enhance muscular performance. The appearance of high BAmm levels during these types of HIIT is considered to be a marker of ATP degradation and energy deficiency in skeletal muscle, as well as the very specific role that phosphagens play during HIIT [11]. It is clear that the metabolic demand of the HIIT requires a high skeletal muscle ATP turnover, which usually results in large reductions in muscle phosphocreatine concentrations [10,24] and in the muscles' ability to match the rate of ATP supply with its rate of utilization, thereby causing a marked reduction of skeletal muscle ATP content [11]. Consequently, the current study provides important information about the utilization of body energy sources during two HIITs by endurance runners, and it confirms that the metabolic impact of both the 10 × 400 m and 40 × 100 m protocols are similar, in spite of differences in running pace.

Another interesting finding of this study is the fact that BLa clearance capacity (obtained from the difference between BLa at 1 min and at 5 min post-test) was more efficient after the 40 × 100 m protocol (BLa was reduced by 3.22 mmol.L^{-1}) than after the 10 × 400 m (reduced by 1.65 mmol.L^{-1}). This finding is highly novel and further research is needed in order to highlight how and why two different HIIT protocols which lead to a very similar metabolic impact show different profiles of BLa clearance. Even though it is known that significant amounts of lactate are removed though gluconeogenesis during rest and exercise [27], it has been established that oxidation is the major metabolic pathway for lactate disposal during both working and recovery periods [28]. In line with this rationale, Thomas et al. [29] suggested that the maximal muscle oxidative capacity is related to the BLa removal ability. Based on the above statements, the authors suggest that the differences in BLa clearance found in the current study might be due to a greater engagement of intracellular oxidative capacity during the 10 × 400 m protocol, which is associated with a longer duration of running.

5. Conclusions

In summary, the changes observed in blood metabolites (BLa and BAmm), as well as the power output changes, and the acute cardiovascular response indicate that 10 × 400 m and 40 × 100 m are two very similar HIIT protocols in terms of metabolic, physiological, and neuromuscular impact. Nevertheless, training differences allow runners to train at a higher pace during the 40 × 100 m. Considering that a growing body of literature points to mean training intensity over a season as the key factor explaining performance improvement, these data suggest that 40 × 100 m might be a more efficient HIIT for improving the performance of endurance runners than the typically performed 10 × 400 m protocol. Moreover, the fact the 40 × 100 m protocol showed a lower RPE score at post-test (lower perceived exertion) together with a better BLa clearance capacity in athletes after the 40 × 100 m reinforces our findings.

From a practical point of view, this study provides useful information for athletes and coaches, demonstrating that splitting interval training into shorter runs increases the average running pace during a HIIT, leading to a similar metabolic, physiological, and neuromuscular response, even when maintaining the same training volume. This finding might have important implications for the training prescription of endurance runners by helping coaches to gain a better understanding the impact of different HIITs have on the athlete.

Although these findings are quite novel and easily applicable to field-work for coaches, more research is needed about the presence of this type of training session over a season.

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Changes in balance ability, power output, and stretch-shortening cycle utilisation after two high-intensity intermittent training protocols in endurance runners

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Original article

Changes in balance ability, power output, and stretch-shortening cycle utilisation after two high-intensity intermittent training protocols in endurance runners

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Abstract

Purpose: This study aimed to describe the acute effects of two different high-intensity intermittent trainings (HITs) on postural control, countermovement jump (CMJ), squat jump (SJ), and stretch-shortening cycle (SSC) utilisation, and to compare the changes induced by both protocols in those variables in endurance runners.
Methods: Eighteen recreationally trained endurance runners participated in this study and were tested on two occasions: 10 runs of 400 m with 90 s recovery between running bouts (10 × 400 m), and 40 runs of 100 m with 30 s recovery between runs (40 × 100 m). Heart rate was monitored during both HITs; blood lactate accumulation and rate of perceived exertion were recorded after both protocols. Vertical jump ability (CMJ and SJ) and SSC together with postural control were also controlled during both HITs.
Results: Repeated measures analysis revealed a significant improvement in CMJ and SJ during 10 × 400 m ($p < 0.05$), whilst no significant changes were observed during 40 × 100 m. Indexes related to SSC did not experience significant changes during any of the protocols. As for postural control, no significant changes were observed in the 40 × 100 m protocol, whilst significant impairments were observed during the 10 × 400 m protocol ($p < 0.05$).
Conclusion: A protocol with a higher number of shorter runs (40 × 100 m) induced different changes in those neuromuscular parameters than those with fewer and longer runs (10 × 400 m). Whereas the 40 × 100 m protocol did not cause any significant changes in vertical jump ability, postural control or SSC utilisation, the 10 × 400 m protocol impaired postural control and caused improvements in vertical jumping tests.

Keywords: Long-distance runner; Postural control; Reactive strength; Training prescription; Vertical jump

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1. Introduction

High-intensity intermittent training (HIT) involves repeated short to long bouts of rather high-intensity exercise interspersed with recovery periods and has been used by athletes for almost a century now.[1] In fact, it is today considered one of the most effective forms of exercise for improving physical performance in athletes.[1,2] Traditionally, this type of training has been associated with sports modalities with high power requirements, although in recent years, a growing body of literature has focused on the benefits of fast intermittent exercises for endurance athletes.[1–3] This fact has enabled both endurance athletes and coaches to realise that both low-intensity training performed at high volumes and high-intensity training of short durations must be part of the training programmes for endurance athletes, and previous papers have shown the effectiveness of training programmes based on both methods.[4,5]

To date, most of research considering HIT in endurance runners has been focused on the acute physiological and neuromuscular response.[3,6–8] However, surprisingly, little attention has been given to parameters such as balance ability and stretch-shortening cycle (SSC) utilisation, which have been associated with both athletic performance and injury risk.[9–13] Indeed, to the best of the researchers' knowledge, no previous study has focused on determining the effect of HITs performed in a real situation—a field study—on postural control and SSC

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utilisation in endurance runners. Therefore, the aims of this study were (1) to describe the acute effects of two different HITs on postural control, countermovement jump (CMJ), squat jump (SJ), and SSC utilisation, and (2) to compare the changes induced by both HIT protocols in the aforementioned variables in endurance runners.

2. Material and methods

2.1. Subjects

A group of 18 recreationally trained endurance runners (age = 30.89 ± 11.69 years, body mass index (BMI) = 22.08 ± 2.17 kg/m^2, velocity associated with VO_{2max} (VVO_{2max}) = 17.24 ± 1.37 km/h), comprising 16 males and two females, voluntarily participated in this study. No general clinical examination was carried out; however, all subjects are medically examined annually. The subjects had trained for about 1–3 h a day, 4–6 days a week all year around, for a minimum of 4 years and had no history of injury in the 3 months before the study, which might have limited training. The study was conducted in November 2014 during cross-country season and during the competition phase of their yearly programme at a time when most of the athletes were at a high level of competitive fitness. At the time of these observations, the athletes had completed between 2 and 4 months of training.

After receiving detailed information on the objectives and procedures of the study, each subject signed an informed consent form to participate, which complied with the ethical standards of the World Medical Association Declaration of Helsinki (2013) and which made it clear that they were free to leave the study if they saw fit. The study was approved by the Ethics Committee of the University of Jaén (Spain).

2.2. Procedures

The participants were asked not to engage in any heavy intensity exercise for 72 h prior to the experiment and to have a meal at least 2 h before beginning warming up. All athletes had experience with the exercises analysed. All training sessions were carried out between 17:00 and 21:00 hours on an outdoor 400 m synthetic track. Before the running exercises, the athletes performed a warm-up, which consisted of 10 min of continuous running and 10 min general exercises (high skipping, leg flexion, jumping exercises, and short bursts of acceleration).

Each athlete was tested on two occasions separated by 7 days: first, 10 runs of 400 m with 90 s recovery between running bouts (10 × 400 m); second, 40 runs of 100 m with 30 s recovery between runs (40 × 100 m). Athletes underwent a passive recovery between runs (just standing, in a vertical position). Both HIT protocols were carried out above the VVO_{2max}, indirectly measured through the velocity of a 3000-m race.[14] Data about each athlete's best time in a 3000-m race the month prior to the test were supplied by their coaches. Participants are experienced athletes who perform these types of workouts in their training programme. So the only instructions were to finish the protocols as fast as they could, maintaining a constant speed as much as possible. No more guidelines were provided as to exercise intensity, apart from the participants being informed that they were to exercise at an intensity of their own choice. Physiological and neuromuscular responses were monitored during both running protocols. The performance in every single run was also recorded (time spent: T400 m and T100 m, respectively, in seconds).

2.3. Materials and testing

2.3.1. Anthropometric variables

Height (m) and body mass (kg) were measured at the beginning of the first testing session; BMI was calculated by means of the following equation: body mass (kg)/height (m^2). A stadiometer (Seca 222; SECA Corp., Hamburg, Germany) and a calibrated bascule (Seca 634; SECA Corp.) were used for this purpose.

2.3.2. Metabolic variables

Blood lactate accumulation (BLa) was recorded during the recovery period, after the last run of each running protocol (BLa at 1 min post-test). For this purpose, fingertip blood samples were analysed with a portable Scout Lactate analyser (SensLab GmbH, Leipzig, Germany). The blood lactate analyser was checked for accuracy according to the manufacturer's instructions prior to every testing session.

2.3.3. Physiological variables

Cardiovascular response was also monitored (Garmin Forerunner 405; Garmin International Inc., Olathe, KS, USA) throughout both 10 × 400 m and 40 × 100 m protocols. Peak heart rate reached (HR_{peak}), average heart rate (HR_{mean}), and heart rate at the end of recovery periods (heart rate recovery, HR_{rec}) were recorded for both running protocols. Moreover, as indicated by Daanen et al.,[15] although HR_{rec} is generally expressed in absolute terms (bpm), it can be useful to express it relative to the HR_{peak} (i.e., the difference between the resting and maximal heart rate) to minimise interpersonal differences. Based on this, the difference between HR_{peak} and HR_{rec} was calculated and was called the heart rate reserve (HRR, measured in bpm). Because the resting periods in both HIT protocols differed, comparing the absolute values of the HR_{rec} and HRR would not be appropriate. Thus, in an attempt to control the impairment of cardiac recovery capacity throughout both running protocols, the difference between the first and the last run (increase, Δ) was used for the statistical analysis. Moreover, in order to obtain further information about the perceived exertion, the rate of perceived exertion (RPE) was recorded on the 6–20 Borg Scale[16] immediately after the last run in both protocols.

2.3.4. Neuromuscular variables

CMJ and SJ tests were performed before (pre-test, unfatigued condition), in the middle of the training session (intermediate test), and after each running workout (post-test, fatigued condition). Participants were experienced athletes who perform different plyometric exercises in their daily training sessions. Moreover, to make sure the execution of the test conducted was correct, a familiarisation session had previously been carried out. The CMJ and SJ were recorded using the OptoGait system (Microgate, Bolzano, Italy), which has been

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previously used in similar studies.[17] This device measures the contact time on the floor and the flight time using photoelectric cells. Flight time was used to calculate the height of the rise using the body's centre of gravity. Subjects performed two trials of every test, with a 15-s recovery period between them with the best trial being used for the statistical analysis. In all tests performed—CMJ, SJ—the pre-intermediate and pre-post differences (increase, Δ) were also calculated and used for the subsequent analysis. Participants were encouraged to achieve maximum performance throughout both running protocols.

Both CMJ and SJ tests are commonly used to discriminate between the effects of the SSC in various athletic populations.[9,18] Performance of the SSC is commonly measured using an added pre-stretch to a movement, such as comparing CMJ performance with SJ performance.[9,18] Researchers have measured SSC performance from CMJ and SJ jump heights as an augmentation of a prior stretch.[19] Pre-stretch augmentation (PSA) can be calculated as a percentage with PSA (%) = ((CMJ − SJ)/SJ) × 100. Another approach is to measure reactive strength (reactive strength index (RSI) calculated as CMJ–SJ height).[20] This is considered to be a measure of the ability to utilise the muscle pre-stretching during the CMJ.[18,20] Intermediate-pre and post-pre differences (Δ) were also calculated for PSA and RSI.

2.3.5. *Postural control variables*

A FreeMed© BASE model baropodometric platform was used for the stabilometric measurements (Sensormédica, Rome, Italy). The platform's surface is 555 × 420 mm, with an active surface of 400 × 400 mm and 8 mm thickness manufactured by Sensormédica. The reliability of this baropodometric platform has been shown in previous studies.[21] Calculations of centre of pressure (CoP) movements were performed with the FreeStep© Standard 3.0 software (Sensormédica). A monopodal stabilometry test was performed before and immediately after (pre- and post-test, respectively) every training session (10 × 400 m and 40 × 100 m). Athletes stood on each of their lower limbs for 10 s (left leg first) at the centre of the platform according to the manufacturer's instructions and following the procedure of previous studies.[22,23] The following parameters were recorded for the left- and right-leg monopodal tests: length (Length) and area (Area) of the path described by the CoP and the speed for the CoP movement (Velocity). The average for both the left- and right-leg was calculated and used for the subsequent analysis.

2.4. *Statistical analysis*

Descriptive statistics are represented as mean ± SD. Tests of normal distribution and homogeneity (Kolmogorov–Smirnov and Levene's) were conducted on all data before analysis. A repeated measures analysis (ANOVA) (pre-, intermediate-, and post-test) was performed for CMJ, SJ, and SSC utilisation variables in both HITs—10 × 400 m and 40 × 100 m—whilst a pre-post comparison was performed by Student's *t* test in variables related to postural control. The level of significance was $p < 0.05$. Data analysis was performed using SPSS (version 21; SPSS Inc., Chicago, IL, USA).

Table 1
HRR, RPE average running pace, and BLa accumulation during two high-intensity intermittent trainings (mean ± SD).

Variable	Protocol		*p* value
	10 × 400m	40 × 100m	
HR_{peak} (bpm)	179.00 ± 9.07	176.25 ± 9.64	0.067
HR_{mean} (bpm)	144.12 ± 14.29	160.60 ± 12.64	<0.001
ΔHR_{rec} (bpm)	31.00 ± 14.09	22.88 ± 14.23	0.091
ΔHRR (bpm)	−13.80 ± 16.55	−3.00 ± 14.36	0.067
RPE (6–20)	16.00 ± 1.24	15.11 ± 1.13	0.019
Running pace (km/h)	18.47 ± 1.51*	21.60 ± 1.72*	<0.001
$\%VVO_{2max}$	107.17 ± 2.83	125.40 ± 4.89	<0.001
BLa (mmol/L)	12.87 ± 3.21	12.40 ± 4.14	0.670

* indicates no significant differences in intra-running protocols, constant speed.
Abbreviations: HRR = Heart rate response; RPE = rate of perceived exertion; BLa = blood lactate at 1 min post-test; HR_{peak} = peak heart rate; HR_{mean} = mean heart rate; ΔHR_{rec} = heart rate recovery in the last run minus HR_{rec} in the first one; ΔHRR = heart rate reserve in the last run minus HRR in the first one; RPE = rate of perceived exertion in a 6–20 scale; $\%VVO_{2max}$ = percentage of velocity associated with maximal oxygen uptake.

3. Results

HRR, RPE, average running pace, and BLa during both HITs (10 × 400 m *vs.* 40 × 100 m) are shown in Table 1. No significant differences were found between running protocols in the HR_{peak}, whilst the HR_{mean} was significantly higher ($p < 0.001$) in the 40 × 100 m protocol. No significant differences between HITs were found in either the ΔHR_{rec} or the ΔHRR. Significant differences between both HITs were found in the RPE ($p = 0.019$), with lower values in the 40 × 100 m protocol. Running pace and $\%VVO_{2max}$ were significantly ($p < 0.001$) faster during 40 × 100 m, and no significant changes were observed in pace throughout both running protocols ($p = 0.670$). The speed maintained during each HIT protocol is shown in Fig. 1. No significant differences in 10 × 400 m or in 40 × 100 m were found. Finally, no significant differences were found in BLa.

Data from the ANOVA of CMJ, SJ, and SSC utilisation throughout both HITs are reported in Table 2. No significant changes were found during the 40 × 100 m protocol, whilst significant improvements in CMJ and SJ ($p = 0.008$ and 0.002, respectively) were found in the 10 × 400 m protocol. Indexes related to SSC utilisation (PSA and RSI) did not experience significant changes during any of the protocols.

A pre-post comparison regarding CoP movement (Area, Length, and Velocity) in monopodal support during both HIT protocols is shown in Table 3. No significant changes were observed in the 40 × 100 m protocol, whilst significant impairments were observed in Area ($p = 0.006$), Length ($p = 0.001$), and Velocity ($p = 0.004$) during the 10 × 400 m protocol.

4. Discussion

The main purpose of this study was to describe the acute effects of two different HITs on postural control, CMJ, SJ, and SSC utilisation in endurance runners, as well as determining whether a protocol with a higher number of shorter runs

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(40 × 100 m) induced different changes in those neuromuscular parameters than those with fewer and longer runs (10 × 400 m). The results obtained showed that despite maintaining the same training volume (4000 m), the difference in training structure enabled runners to train at a higher running pace (+3.13 km/h) during the 40 × 100 m protocol. Additionally, the acute effect of both HITs on postural control and power output differed, whilst SSC utilisation remained unchanged throughout both HITs. Whereas the 40 × 100 m protocol did not cause any significant changes in vertical jump ability, postural control or SSC utilisation, the 10 × 400 m protocol impaired postural control (from 18.33% to 40.83% impairment in CoP movement) and caused improvements in CMJ (+5.18%) and SJ (+6.43%). Moreover, the evolution of the cardiovascular response (HR_{peak}, 10 × 400 m: 179.00 bpm; 40 × 100 m: 176.25 bpm) and lactate accumulation levels (BLa, 10 × 400 m: 12.87 mmol/L; 40 × 100 m: 12.40 mmol/L) during both HIT protocols indicate that high exhaustion levels were reached with no significant differences between both HITs. This fact eliminates and negates the possibility that acute response differences in both HITs might be due to athletes' levels of involvement or exhaustion levels induced by both HITs. It is also worth noting that athletic performance in terms of running pace was not impaired during any of HITs, so athletes followed the instructions given by coaches and they were able to maintain the speed and to be regular during both protocols.

Both metabolic markers and vertical jumping height are of interest because they are considered to indirectly reflect the degree of anaerobic glycolysis activation (BLa),[24] as well as

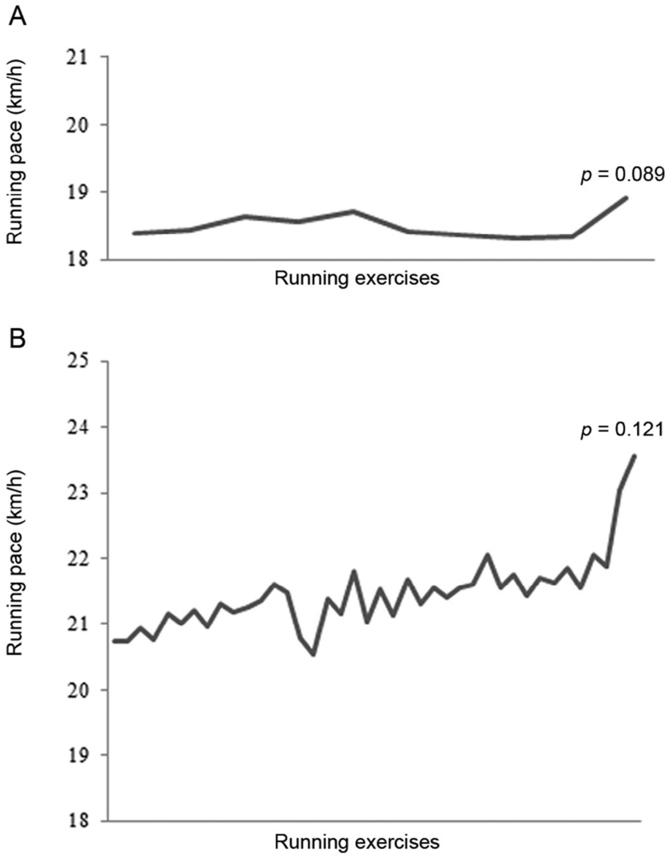

Fig. 1. Running pace during both high-intensity intermittent training protocols: 10 × 400 m (A) and 40 × 100 m (B).

Table 2
Repeated measures analysis of CMJ, SJ, and SSC utilisation in both high-intensity intermittent protocols (mean ± SD).

Variable	Protocol	Pre-test	Intermediate test	Post-test	Intermediate-pre difference (Δ, %)	Post-pre difference (Δ, %)	*p* value
CMJ (cm)	10 × 400 m	27.11 ± 4.56[a]	27.99 ± 3.44	28.59 ± 4.84[a]	0.88 (3.14)	1.48 (5.18)	0.008
	40 × 100 m	28.25 ± 4.23	28.32 ± 4.80	27.91 ± 4.64	0.07 (0.25)	−0.34 (−1.20)	0.581
SJ (cm)	10 × 400 m	25.60 ± 4.51[a]	26.76 ± 4.20	27.36 ± 4.54[a]	1.16 (4.33)	1.76 (6.43)	0.002
	40 × 100 m	27.87 ± 4.21	28.02 ± 3.89	27.47 ± 4.21	0.15 (0.54)	−0.40 (−1.44)	0.374
PSA (%)	10 × 400 m	6.19 ± 5.51	5.36 ± 8.32	4.65 ± 7.92	−0.83 (−13.41)	−1.54 (−24.88)	0.638
	40 × 100 m	3.41 ± 5.16	0.90 ± 7.29	1.48 ± 4.29	−2.51 (−73.61)	−1.93 (−56.60)	0.484
RSI (cm)	10 × 400 m	1.51 ± 1.34	1.24 ± 2.24	1.23 ± 1.99	−0.27 (−17.88)	−0.28 (−18.54)	0.721
	40 × 100 m	0.85 ± 1.24	0.30 ± 2.07	0.44 ± 1.21	−0.55 (−64.71)	−0.41 (−48.24)	0.592

Note: *p* value indicates differences within protocols.

[a] The same superscript letter indicates significant differences within protocol (repeated measures analysis).

Abbreviations: CMJ = countermovement jump; SJ = squat jump; SSC = stretch-shortening cycle utilisation; PSA = pre-stretch augmentation; RSI = reactive strength index.

Table 3
Pre-post comparison regarding CoP movement in monopodal support (average from both the left and the right sides) during high-intensity intermittent protocols (mean ± SD).

Variable	Protocol	Pre-test	Post-test	Post-pre difference (Δ, %)	*p* value
Area (mm)	10 × 400 m	417.80 ± 201.47	706.10 ± 403.31	288.30 (40.83)	0.006
	40 × 100 m	835.30 ± 584.08	910.27 ± 1163.35	74.97 (8.24)	0.812
Length (mm)	10 × 400 m	338.72 ± 74.08	414.75 ± 116.85	76.03 (18.33)	0.001
	40 × 100 m	385.72 ± 103.67	436.30 ± 167.84	50.58 (11.59)	0.220
Velocity (mm/s)	10 × 400 m	24.02 ± 6.04	29.73 ± 10.63	5.71 (19.21)	0.004
	40 × 100 m	29.13 ± 9.25	33.43 ± 18.61	4.30 (12.86)	0.364

Abbreviations: CoP = centre of pressure; Area = area of centre of pressure movement in monopodal support; Length = length of centre of pressure movement in monopodal support; Velocity = velocity of centre of pressure movement in monopodal support.

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the capability of the leg extensor muscles to generate mechanical power (CMJ and SJ).[25] This study showed that in spite of the high level of fatigue reached—as demonstrated by cardiovascular response, BLa and RPE—the vertical jump ability was not impaired after HITs in endurance runners. In the 40 × 100 m protocol the CMJ and SJ performance remained unchanged—there were no significant differences according to baseline values. Even more surprising was that the best values for CMJ and SJ performance for the 10 × 400 m protocol were obtained post-test. It might be expected that power performance after running exercises inducing high levels of fatigue would decreased. Nevertheless, some previous studies[6,7,26,27] found post-activation potentiation (PAP)—a significant improvement in muscular power as a result of previous muscular work[28,29]—after running exercises in endurance runners. These data show that, despite high levels of fatigue, trained subjects can maintain their strength and power levels, and therefore their work capacity in terms of running pace, during HIT protocols performed above VVO_{2max}. Since fatigue level after both workouts was similar and pace was maintained over both HITs, neither level of fatigue reached nor pacing strategy for each HIT seems to be responsible for changes induced in jumping ability. The authors suggest that the running pace might be responsible for these muscle power output changes. A faster running pace during the 40 × 100 m protocol (faster average pace and higher $\%VVO_{2max}$) will recruit additional fast twitch motor units for relatively short durations.[30]

Data obtained from SSC utilisation support and reinforce that statement. It might be expected that SSC utilisation, indirectly measured by means of PSA and RSI, would decrease throughout both HITs. Despite a trend towards lower SSC utilisation being observed in both HITs, no significant changes were found in PSA or RSI during either running protocols. As far as the authors know, the information available about SSC utilisation in endurance athletes is limited[18,31,32] and no previous studies have analysed the fatigue-induced changes in SSC utilisation during running exercises so the comparison with previous studies is quite difficult. Padua et al.[33] concluded that some parameters associated with SSC utilisation were unaffected after fatigue, the opposite results found by Moritani et al.[34]

Basic muscle function is defined as the SSC, where the pre-activated muscle is first stretched (eccentric action) and then followed by the shortening (concentric) action.[35] However, neuromuscular fatigue has traditionally been examined using isolated forms of isometric, concentric or eccentric actions, whereas none of these actions are naturally occurring in human ground locomotion. Parameters related to SSC utilisation, such as PSA or RSI, have been used for monitoring training adaptations over a sport season[18] and have been associated with performance enhancement, injury prevention and fatigue mechanisms.[12,33,36] Based on the results obtained, the authors suggest that monitoring parameters such as RSI and PSA during running exercises might provide interesting information about acute responses to training sessions and about training adaptation throughout the season.

Postural control is a complex function that involves keeping the vertical projection of the centre of gravity within the base of support.[11] As indicated by Degache et al.[37] postural control is a permanent re-establishment process of balance, which depends on the orientation information derived from three independent sensory sources: somatosensory, vestibular, and visual inputs. Balance is actively controlled by the central nervous system, which calls into action various relevant postural muscles when they are required;[38] therefore, postural control is also dependent upon reflexive and voluntary muscle responses.[39] On the other hand, fatigue following physical exercise is caused by a combination of physiological processes, occurring at both central and peripheral levels, which mainly deal with the inability to produce an expected force or with the increase in the onset delay of movement.[30] It has been shown that exercises such as running, cycling, cycle ergometer, walking, ironman triathlon, or mountain ultra-marathon affect postural control.[22,37–39] This type of exercise involving the whole organism deteriorates the sensory proprioceptive and exteroceptive information and/or their integration, and/or decreases the muscular system efficiency.[38] It is therefore well documented that muscular exercise is a cause of aggravation of postural sway since the increase of energy needs amplifies liquid movements and cardiac and respiratory muscular contractions.[40] In addition, when muscular exercise generates fatigue, it affects the regulating system of postural control by its effects on the quality and treatment of sensory information, as well as motor command. Indeed, muscular exercise induces perturbations of the neuromuscular system that involve changes in muscle strength[7] and postural control.[22]

As for balance ability and fatigue-induced changes by two different HITs in endurance runners, the data obtained in this study are partially consistent with previous works showing that CoP movements in monopodal support were greater—worse balance ability—after two different HITs (10 × 400 m: 18.33%–40.83% and 40 × 100 m: 8.24%–12.86%) according to pre-test or baseline values. Nevertheless, despite no differences being found between fatigue levels induced by either HIT protocols, reductions only were statistically significant after the 10 × 400 m protocol, whilst no significant reductions were seen in the 40 × 100 m protocol. To date, previous papers focused on checking the fatigue-induced changes after running exercises in balance ability reported impairment.[22,37,40] However, as indicated by Degache et al.,[37] the conditions under which the different exercises are performed influence postural control in different ways. As mentioned earlier, neither level of fatigue reached nor pacing strategy for each HIT seems to be responsible for changes induced in balance ability. However, this study seems to indicate that short runs performed at high intensities (40 × 100 m) cause smaller impairments in postural control than longer runs performed at a slower pace (10 × 400 m). Anyway, more research is needed to highlight the physiological basis of that assumption.

Finally, the main limitation of this study was not to include more indications on a precise intensity to maintain. Despite that VVO_{2max} was reported, coaches usually prescribe in terms of $\%HR_{max}$ or best performance on a distance. Notwithstanding

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this limitation, the study offers some insight into neuromuscular impact of HIT in endurance runners and training method selection for endurance runners by comparing two running sessions of the same overall volume (4 km) but distributed differently (10 × 400 m or 40 × 100 m).

5. Conclusion

To sum up, the results obtained in this study showed that acute effects of both HITs on postural control and power output differed, whilst SSC utilisation remained unchanged throughout both HITs. Whereas the 40 × 100 m protocol did not cause any significant changes in vertical jump ability, postural control, or SSC utilisation, the 10 × 400 m protocol impaired postural control (in terms of CoP movement) and caused improvements in vertical jumping tests. Hence, a protocol with a higher number of shorter runs (40 × 100 m) induced different changes in those neuromuscular parameters than those with fewer and longer runs (10 × 400 m). Likewise, data showed that, despite maintaining the same training volume and inducing similar levels of fatigue, the difference in training structure enabled runners to train at a higher pace during the 40 × 100 m protocol. Based on this, the authors accentuate the importance of average running pace in every workout, leading to different fatigue-induced changes in power output and postural control despite maintaining the training volume and inducing similar levels of fatigue.

From a practical point of view, a further knowledge about the acute impact of different HITs on the neuromuscular system of endurance runners might facilitate a higher accuracy in training prescription for coaches. Additionally, the fact that trained subjects can maintain their strength and power levels and, therefore, their work capacity during HITs performed above VVO_{2max} and inducing high levels of fatigue, might provide useful and interesting information for coaches and athletes about training adaptations throughout the sport season. The authors therefore suggest that monitoring parameters such as CMJ, SJ, SSC utilisation, and balance ability during running exercises might provide practical information about both acute responses to training sessions and training adaptation.

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Authors' contributions

FGP participated in the data collection, performed the statistical analysis and drafted the manuscript; JAPM participated in the data collection and in its design and revised the manuscript critically; VMSH participated in the data collection and in its design and revised the manuscript critically; PALR participated in the data collection and in its design and revised the manuscript critically.

Competing interests

None of the authors declare competing financial interests.

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Kinematic alterations after two high-intensity intermittent training protocols in runners

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Submitted

Kinematic alterations after two high-intensity intermittent protocols in runners

Short title: HIIT and running kinematics

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ABSTRACT

Purpose: To evaluate running kinematic characteristics during early and late stages of two high-intensity intermittent (HIIT) protocols for endurance runners.

Methods: Eighteen recreationally trained endurance runners were tested on two occasions: 10 runs of 400 m with 90-120-s recovery between running bouts (10×400m), and 40 runs of 100 m with 25-30-s recovery between runs (40×100m). Heart rate (HR) was monitored during both protocols; blood lactate accumulation (BLa) and rate of perceived exertion (RPE) were recorded after both exercises. A high-speed camera was used to measure sagittal-plane kinematics at the first and the last run during both HIIT protocols. The dependent variables were spatial-temporal parameters, joint angles during support, and foot strike pattern.

Results: High levels of exhaustion were reached by the athletes during both workouts (BLa>12 mmol.l^{-1}; RPE>15; HR$_{peak}$>176 bpm). A within-protocol paired t-test (first vs. last run) revealed no significant changes ($P \geq 0.05$) in kinematic variables during any of the HIIT sessions. A between-protocol comparison with the first run of each protocol revealed the effect of running speed on kinematics (+2.44 km.h^{-1} during the 40x100m: shorter contact and flight time, and longer step length; greater hip flexion and lower ankle flexion at initial contact; lower knee and ankle flexion at mid-stance; greater hip extension at toe-off).

Conclusion: HIIT sessions including runs for 15-90 seconds and performed at intensity above velocity associated to maximal oxygen uptake, did not consistently perturb the running kinematics of trained endurance runners. Since previous studies had suggested that 40×100m might be a more efficient HIIT for improving the performance of endurance runners, this study reinforces that statement with no kinematic alterations during any of those running exercises.

Keywords: fatigue-induced changes; interval training; long-distance runners; running technique

1. INTRODUCTION

High-intensity intermittent training (HIIT) is considered one of the most effective forms of exercise for improving the physical performance of athletes (3, 4, 7, 31), and its effectiveness has been widely studied in endurance runners (17, 20). Compared with lower intensity cyclic workloads, intensive running requires the activation of larger motor units, with increased recruitment of fast oxidative and glycolytic muscle fibres, and the increase of the intensity of chemical processes in the muscle which exert a direct influence on the contractile ability of the muscle (32, 36). Additionally, increases in running speed lead to higher impact forces imposed on the lower limbs (24) and greater levels of neuromuscular engagement (mainly in the hamstring muscles) (23). The concomitant increase in muscle acidity and decrease in phosphagen stores with muscle fatigue alters muscle force generation capabilities (10), which may be linked to changes in joint movement patterns (12, 14, 15, 21, 33) and in running mechanics (2), which are often linked to running injury (2, 35). Therefore, despite the lack of prospective studies evaluating injury occurrence, knowing the acute changes in running kinematics during HIIT workouts seems to play a key role in terms of injury management and training prescription.

The effect of exertion on running kinematics has been extensively studied (1, 2, 11, 12, 14, 15, 21, 30, 33). Some previous studies reported non-significant running kinematic alterations after different running exercises (1, 12, 22), whereas other works found fatigue-induced changes during running at kinematic level - i.e. increased hip extension (27), decreased knee flexion angle at foot strike (33), increase in step length with a corresponding decrease in cadence (21), and changes in foot strike pattern (29, 30). However, most of these studies were performed in laboratory conditions and with athletes performing prolonged treadmill runs (15, 21, 33), or running-induced fatigue protocol on treadmills (1, 10, 14). Just a few studies have been field-based (11, 22, 30), although all of them were focused on long-distance road racing. The evidence of changes induced by intermittent running protocols is quite limited. From all these studies, only two works (12, 38) assessed HIIT-induced changes to the biomechanics of running. Both agreed that HIIT sessions including runs for 1–2 min and performed at intensity close to maximal oxygen uptake (VO_{2max}), did not consistently perturb the running kinematics of trained male runners.

Coaches have questioned whether it would be more effective to perform a higher number of shorter runs, or a few long runs during a HIIT workout. It seems clear that changes in the training load during HIIT protocol (in terms of intensity, volume and density) will challenge both the metabolic and the neuromuscular systems at different levels. Many variables, at least nine, can be manipulated to prescribe different HIIT sessions and among them the intensity and duration of work and relief intervals are the key influencing factors (7, 8, 37). Likewise, the role of mean training intensity over a season in optimising athletic performance has been extensively documented (3, 4, 7, 8, 31). Thus, taken together, the key point for coaches and athletes is whether at the same absolute training load/volume it is possible to increase the average training pace by modifying other variables, such as intensity or the number of runs, without changing the physiological and neuromuscular impact and without altering dangerously (in terms of risk of injury) running kinematics. In this context, some previous studies (18, 19) have tried to answer that question, and reported similar acute physiological response to two HIIT workouts (10x400m vs. 40x100m) with identical volume (4 km), similar Work:Rest ratio (0.65 and 0.67 respectively) but with significant differences in average pace (+3.13 $km.h^{-1}$ during 40x100m). Likewise and despite differences in mean velocity, the aforementioned studies (18, 19) reported no impairments in muscular performance parameters after training. What is still unknown is whether the difference in mean velocity will lead to different alterations in running kinematics.

Therefore, the main goal of this study is to evaluate running kinematic characteristics during the early and late stages of two HIIT protocols for endurance runners (10x400m vs. 40x100m). The authors hypothesised that due to the high level of exhaustion reached during these HIIT protocols, running kinematics might change between the first and last runs. Additionally, focused on a between-protocol comparison, the differences reported by previous studies in the neuromuscular response to both protocols might cause different kinematic alterations during 10x400m and 40x100m.

2. METHODS

A crossover study design was used to determine the fatigue-induced changes in running kinematic of endurance runners during two HIIT protocols, performed on a track by endurance runners.

2.1. Subjects

A group of eighteen recreationally trained endurance runners (age=30.9±11.7 years; body mass index [BMI]=22.1±2.2 kg/m^2; 16 males and 2 females) voluntarily participated in this study. No general clinical examination was carried out, but all subjects were medically examined annually. The subjects had trained for 1–3 hours a day, 4–6 days a week all year round for a minimum of four years and had no history of an injury in their three months before they participated. The study was conducted in November 2014 during the cross-country season and the competition phase of their yearly program, at a time when most of the athletes were at a high level of competitive fitness. At the time of these observations, the track athletes had completed between two and four months of training for that season. More information about the participants is presented in Table 1.

TABLE 1 ABOUT HERE

After receiving detailed information on the objectives and procedures for the study, each subject signed an informed consent form to participate, which complied with the ethical standards of the World Medical Association's Declaration of Helsinki (2013) and made clear that they were free to leave the study if they saw fit. The study was approved by the Ethics Committee of the University of Jaen (Spain).

2.2. Procedures

The participants were asked not to engage in any high intensity exercise during the 72 hours before the experiment and to have a meal at least two hours before the beginning of warm up. All athletes had experience with the exercises to be analysed. All the training sessions were carried out between 17:00 and 21:00 hours on an outdoor 400-m synthetic track. Before the running exercises, the athletes performed a standardised warm up and then, five 13-mm diameter retro-reflective markers (fifth metatarsal, lateral malleolus, lateral epicondyle of the femur, greater trochanter, and acromion) were placed on the right-side of the body (Figure 1). These landmarks defined the positions of upper body (head, arms and trunk being taken together), lower legs and feet. After markers placement, the participants began the running protocol.

FIGURE 1 ABOUT HERE

Each athlete was tested on two occasions, separated by seven days: (1) ten runs of 400 m with 90-120 s of recovery between running bouts (10×400m); (2) 40 runs of 100 m with 25-30 s of recovery between runs (40×100m). Both running exercises show the same volume (4000 m), similar percentage of total training time in which athlete is working (39.5% and 40.7% respectively) and Work:Rest ratio -coefficient between work period and rest period- (0.65 and 0.67 respectively). In order to avoid "an order effect" the protocol was counterbalanced. Both HIIT protocols were carried out above the velocity associated with

VO_{2max} (VV_{O2max}), which was indirectly measured from the velocity of a 3000 m race (25). A passive recovery between runs was undertaken during both HIIT protocols, as they stood upright. Participants are experienced athletes who performed these types of workouts in their training program so, the only instructions were to finish the protocols as fast as they could as they maintained a constant speed to the best of their ability. No more guidelines were provided as to exercise intensity, though subjects were informed to run at self-selected exercise intensities. The physiological response was monitored during both running protocols and videos were recorded from a sagittal plane in the first and last run of both protocols. The performance of every single run was also recorded through time spent.

Materials and testing

Anthropometric variables: Height (m) and body mass (kg) were measured at the start of the first testing session, whilst BMI was calculated by means of the following equation: body mass (kg)/ height (m^2). A stadiometer (Seca 222, Hamburg, Germany) and a calibrated bascule (Seca 634, Hamburg, Germany) were used for that purpose.

Physiological variables: In order to monitor the physiological demands of both HIIT protocols, the cardiovascular response was monitored throughout the exercise, using the Garmin Forerunner monitor 405 (KS, USA). The peak heart rate achieved and the recovery heart rate at 1 min (HRpeak and HRrec, respectively) were used for the analysis. Additionally, blood lactate accumulation (BLa, $mmol.l^{-1}$), and the rate of perceived exertion (RPE) were also recorded after the last run of the running exercise, and for this purpose, a portable lactate analyser (Lactate-Pro, Arkray, Inc.), and the 6-20 Borg Scale (5) were used.

Athletic performance: The time spent in each run (s) was also recorded during both workouts. The variables used for subsequent analysis were the average running pace of the whole protocol (T400m and T100m, in $km.h^{-1}$).

Kinematics: A sagittal-plane video (240 Hz) of the first and the last run during both HIIT protocols was recorded using a high-speed camcorder (Casio Exilim EXF1, Shibuyaku, Tokyo 151–8543, Japan). Videos were taken from a lateral view, with the camera perpendicularly placed five metres from the runner so that they could be filmed in the sagittal plane. Filming location was set at the end of the 400-m run, 20 metres before the finish line. For each runner, a complete stride cycle was captured on film, and kinematic variables were measured for the right leg. Video data were analysed using a 2D video editor (VideoSpeed vs1.38, ErgoSport, Granada, Spain).

The dependent variables selected for the kinematics analysis are in accord with previous works (11, 13, 21, 22, 30) and are presented below:

i) Relative angle of the hip, knee and ankle (θhip, θknee and θankle, respectively) at three key points during support: (a) the initial contact (first visible point during stance where the athlete's foot clearly contacts the ground); (b) at mid-stance (the maximum knee flexion in the support phase); (c) at toe-off (the last frame with ground contact). θhip was defined as the sagittal plane angle between the trunk and thigh segments and was considered to be 180º in the anatomical standing position. The θknee was calculated as the sagittal plane angle between the thigh and leg segments and was also considered to be 180º in the anatomical standing position. The θankle was calculated in a counterclockwise direction using the leg and foot segments (21, 22).

ii) Spatial-temporal parameters: step length – distance from one foot strike to the next foot strike of the opposite foot (SL, in metres); and contact and flight time – the time duration from initial contact to toe-off, whereas flight time was the time duration from toe-off of one foot contact to the initial contact of the opposite foot (CT and FT respectively, in seconds).

iii) Foot strike pattern (FSP) at first contact with the ground, on a 1-5 scale of severity (30), from rearfoot to forefoot: 1) high rearfoot strike – landing with the second half of the heel (the landing from the back of the heel); 2) rearfoot strike – the ball of the foot landing before the heel; 3) midfoot – the landing of the heel and sole simultaneously; 4) forefoot – landing with the ball of the foot; 5) and high forefoot strike – the ball of the foot made contact with the ground (no contact with the heel, running on tiptoe).

2.4. Statistical Analysis

Descriptive statistics are represented as means (SD) and percentages. Tests for normality and homogeneity of variances (Shapiro-Wilk and Levene's, respectively) were conducted on all data before analysis. Paired t-test was used to compare running kinematic parameters at first run during both HIIT protocols (between groups comparison). Paired t-test was also used to compare the analysed variables at the beginning and at the end of both HIIT protocols (within-group comparison: 1st run vs. 12th run during the 10x400 m, and 1st run vs. 40th run during the 40x100 m). As for the FSP, the within-group equality of proportions (first vs. last run) was checked through McNemar test. A repeated measures analysis of variance (ANOVA), with post-hoc Bonferroni’s test, was performed for running pace throughout both HIIT workouts (within protocol, to determine if changes in pace were found during both protocols). Reliability intra- and inter-observer was calculated for FSP (due to an observational method was used) using the Cohen’s Kappa coefficient (28). The level of significance was set at $P < 0.05$. Data analysis was performed using SPSS (version 21, SPSS Inc., Chicago, Ill).

3. RESULTS

Reliability intra-observer and inter-observer was calculated using Kappa of Cohen for FSP (intra-observer – Kappa = 0.923, proportion of agreement = 95%; inter-observer – Kappa = 0.851, proportion of agreement = 95%).

Heart rate response, BLa, RPE and average running pace in both exercises are presented in Table 2. No significant differences between running protocols ($P \geq 0.05$) were found for either HRpeak or ΔHRrec, whilst the HRmean was significantly higher ($P < 0.001$) in the 40×100 m. No significant differences ($P = 0.670$) were found in BLa at 1 minute post-exercise. Significant differences between both HIIT exercises were found for RPE ($P = 0.019$), with lower values in the 40×10m. Likewise, significant differences ($P < 0.001$) between protocols were also found in running pace or %VVO_{2max} ($P < 0.001$), with a faster average pace in the 40×100 m (~3 $km.h^{-1}$). Finally, the repeated measures analysis showed no significant differences between the time spent in each run throughout both 10×400 m ($P = 0.089$) and 40×100 m ($P = 0.121$) protocols.

TABLE 2 ABOUT HERE

Since both protocols were performed at different velocities ($P < 0.001$), Table 3 shows the effect of running velocity on running kinematics by comparing the first run in every protocol (10x400m vs. 40x100m). An increased running velocity during the 40x100m protocol yielded a decreased CT (13.02%) and FT (8.85%) and an increased SL (3.87%), as well as some differences in joint angles: at initial contact – a greater hip flexion (2.73%) and ankle extension (7.4%); at midstance – smaller knee and ankle flexion (3.9 and 8.75% respectively); and at toe-off – a higher hip extension (19.8%).

TABLE 3 ABOUT HERE

Running kinematic alterations during both HIIT protocols are shown in Table 4 (joint angles) and Figure 2 (spatial-temporal parameters). No significant changes ($P \geq 0.05$) were found during the 10x400m or the 40x100m protocol.

TABLE 3 ABOUT HERE

FIGURE 2 ABOUT HERE

Regarding the FSP (Figure 3), no significant differences ($P \geq 0.05$) were found between protocols during the first run ($P = 0.135$). No significant alterations were found in the FSP during 10x400m ($P = 0.392$) or 40x100m ($P = 0.317$) protocols.

FIGURE 3 ABOUT HERE

4. DISCUSSION

The acute physiological and metabolic response (19) and the neuromuscular response (18) to both 10x400m and 40x100m protocols have been previously determined. The results reported by these studies showed that 10×400m and 40×100m are two very similar HIIT protocols in terms of metabolic and physiological impact, with similar responses in terms of blood metabolites and cardiovascular response (19). Some minor differences between both HIIT protocols were found in the neuromuscular response, measured through the acute effect of both HIIT workouts on postural control and power output measurements (18). Nevertheless, no previous studies have investigated the impact of these HIIT protocols at kinematic level and, thus, this study aimed to evaluate running kinematic characteristics during the early and late stages (first vs. last run) of the aforementioned HIIT protocols (10x400m vs. 40x100m).

In this context, the major finding of this study was that, despite the high-level of exhaustion reached by the athletes during both workouts (BLa>12 mmol.l^{-1}; RPE>15; HR$_{peak}$>176 bpm), these HIIT protocols did not consistently perturb the running kinematics of trained endurance runners. No significant changes were observed in joint angles, spatial-temporal parameters, or FSP during both HIIT protocols, which rejects the initial authors´ hypothesis. Despite the suggestion that fatigue could alter biomechanical and neuromuscular function in a manner that could possibly lead to an increased risk of sustaining musculoskeletal injury, and/or impaired performance (26), this finding is consistent with some previous studies that did not report alterations in the running kinematics after different running exercises (1, 12, 22). However, not all studies on this topic are in agreement and other works have found fatigue-induced changes during running at a kinematic level (14, 15, 21, 27, 33). For example, Mizrahi (33) found an increase in knee angle at maximal knee extension and a decrease in knee flexion angle at foot strike after 30 min continuous running at anaerobic threshold. Focusing on spatial-temporal parameters, some studies (21, 33) have reported changes after continuous runs - increased SL with a corresponding decrease in cadence, and decreases in CT occurred in conjunction with increases in FT. It is worth noting that the protocols used in these studies are different so that results are quite difficult to compare and consensus has not yet been reached. As we indicated earlier, just two studies have analysed running kinematics during interval training (12, 38) and, even though the running protocol and the controlled variables are not exactly the same, the main findings are in line with our study. Based on our findings and on the results from similar studies, the authors suggest that, at least in experienced endurance runners, HIIT workouts do not impair running kinematics despite the high levels of fatigue accumulated.

Another interesting finding in the current study was the lack of significant changes in FSP during both protocols (10x400m and 40x100m). The relationship between FSP and running economy, performance and injury rates in endurance runners has been documented in recent literature (13, 30). From the perspective of injury, it has been suggested, on the one hand, that the risk of injury can be diminished by reducing the magnitude of impact forces, which can be achieved by adopting midfoot or forefoot strikes (13). On the other hand, compared to rearfoot, forefoot strikes cause higher joint moments in the ankle, although lower in the knee and hip, which might increase the risk of Achilles tendinopathies, injuries of the foot, and stress fractures of the metatarsals (13). Whilst it is not known if higher joint moments cause injuries, it is clear that the most important difference between rearfoot and forefoot strike, from the perspective of injury, is the nature of the impact peak at the initial contact (13).

Some previous papers have examined FSP during long-distance road competition (11, 29, 30) and concluded that, in presence of fatigue, FSP tends to change by diminishing the frequencies of forefoot and increasing midfoot and rearfoot strikes. To the best of the authors' knowledge, no previous studies have examined the fatigue-induced changes in FSP during a HIIT protocol which makes a comparison difficult. Anyway, since the influence of fatigue on the FSP has been previously established (13), and a growing body of literature points to rearfoot as an injury risk factor for endurance runners (13), the lack of changes in FSP after HIIT protocols is an important finding.

Finally, given the between-protocols difference in running velocity and the influence of this variable on running kinetics and kinematics (6, 10, 11, 13, 30), the authors decided to incorporate a between-protocol comparison in unfatigued conditions (at first run of every protocol, with +2.44 km.h^{-1} during the 40x100m). As for the spatial-temporal parameters, it seems clear that to run faster, CT need to be decreased to aid in repositioning the legs during running (6) and the results obtained support that statement, with shorter CT during the 40x100m protocol (~13%). More controversial is the dynamic of SL when velocity increases. It has been suggested that SL increases linearly with running velocity up to 25 km.h^{-1} (6), which is in consonance with our findings (SL ~4% longer during the faster protocol).

Regarding the effect of running speed on joint angles, our findings are consistent with previous works (6, 10, 11, 13, 30) and some differences between faster and slower runs were found in the unfatigued condition – increased running velocity led to a greater hip flexion and lower ankle flexion at initial contact, lower knee and ankle flexion at midstance and greater hip extension at toe-off. These differences appear to be totally logical since lower ankle flexion at initial contact has been related to a shorter CT (6, 13), and lower knee and ankle flexions at midstance have been associated to shorter CT and higher leg stiffness, all of them key factors in running performance (14, 16, 34). Increased hip flexion at initial contact provides better dynamic stability and has been previously associated to running velocity (9), even though it may increase abnormal stress on the lower-extremity joints and further fatigue the lower-extremity muscles and increase the risk of injury (6, 9, 15).

The difference in running velocity has been also demonstrated to influence FSP (13, 30). Despite the lack of differences in FSP between both protocols (10x400m vs. 40x100m), the results obtained provide support to the above statement, obtaining a higher prevalence of midfoot and forefoot (~22% forefoot and ~28-33% midfoot, averaged from both HIIT protocols) than previous studies where athletes ran at slower velocities (~87-95% rearfoot) (29, 30). Therefore, the lack of differences between protocols reported by the current study might be due to the high velocity reached during both HIIT protocols.

A limitation of the present study is that we focused only on sagittal-plane movements. It is likely that fatigue causes alterations in movements in the frontal and transverse planes. Another limitation is that subjects might run asymmetrically between left and right lower extremities, however, only the right leg was analysed. For future reference, setting more cameras on both sides of the race and from different planes could minimise some of these limitations and increase validity. Obviously, all these limitations are related with the use of a two-dimensional motion analysis. However, notwithstanding these limitations, the current field-based study offers some insight into the running kinematic alterations during typical HIIT protocols for endurance runners and provides helpful data for coaches and athletes.

To sum up, the results obtained showed that HIIT sessions including runs for 15-90 seconds and performed at intensity above velocity associated to maximal oxygen uptake, did not consistently perturb the running kinematics of trained endurance runners. Additionally, a comparison made between runs performed at different velocities and in un-fatigued conditions revealed some differences in spatial-temporal parameters and joint angles that must be taken into consideration when the intensity of running exercises is prescribed. Finally, focusing on the 10x400m vs. 40x100m comparison and since previous studies had suggested that 40×100m might be a more efficient HIIT for improving the performance of endurance runners - due to a faster average running pace with similar physiological and neuromuscular response, this study reinforces that statement, with no kinematic alterations observed during any of those running exercises.

From a practical point of view, this study indicates that coaches and runners need not fear substantial detrimental effects from HIIT protocols on running technique. Such information is essential for the design of more effective training programmes for injury prevention and performance enhancement in running. Knowledge about the effect of every training session on the athlete plays a key role in proper training prescription, which means that a further description of the impact of the most typical running exercises on endurance runners is needed, which can lead to better understanding and accuracy in the training prescription process. Additionally, since most injuries in running can be attributed to overuse from repeated bouts of activity, more evidence is needed about the cumulative effects of HIIT-based running sessions.

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Conflicts of Interest and Source of Funding

None declared

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Table 1. Anthropometric characteristics and training background of participants (mean ± SD, n = 18).

Age (years)	Body mass (kg)	Height (m)	BMI (kg/m^2)	Training experience (years)	VVO$_{2max}$ (km.h^{-1})
30.89 ±11.69	65.78 ± 9.02	1.72 ± 0.06	22.08 ± 2.17	7.00 ± 2.61	17.24 ± 1.37

BMI: body mass index; VVO$_{2max}$: velocity associated to maximal oxygen uptake

Table 2. Heart rate response, lactate accumulation, rate of perceived exertion and average running pace during two high-intensity training protocols (10×400m and 40×100m)

Variables	10x400m *Mean (SD)*	40x100m *Mean (SD)*	*p-value*
HRpeak (bpm)	179.00 (9.07)	176.25 (9.64)	0.067
HRmean (bpm)	144.12 (14.29)	160.60 (12.64)	<0.001
ΔHRrec (bpm)	31.00 (14.09)	22.88 (14.23)	0.091
BLa (mmol.L^{-1})	12.87 (3.21)	12.40 (4.14)	0.670
RPE (6-20)	16.00 (1.24)	15.11 (1.13)	0.019
Running pace (km.h^{-1})	18.47 (1.51)$^{\wedge}$	21.60 (1.72)$^{\wedge}$	<0.001
%VVO_{2max} (%)	107.17 (2.83)	125.40 (4.89)	<0.001

^ indicates no significant differences within-running protocols, constant speed; 10x400m: 10 runs of 400-m with 90-120 s of recovery between running bouts; 40x100m: 40 runs of 100-m with 25-30 s of recovery between runs; HRpeak: peak heart rate; HRmean: mean heart rate; ΔHRrec: heart rate recovery in the last run minus HRrec in the first one; BLa: blood lactate accumulation; RPE: rate of perceived exertion in a 6-20 scale; %VVO_{2max}: percentage of velocity associated to maximal oxygen uptake.

Table 3. Comparative analysis of running kinematics during the first run (unfatigued condition) of both running protocols (10x400m vs. 40x100m) performed at different running velocities

Variables	10x400m	40x100m	%Δ	*P-value*	95% CI
Running velocity (km.h^{-1})	18.40 (1.48)	20.84 (1.49)	↑13.26	<0.001	-3.20/-1.68
Spatial-temporal parameters					
Contact time (s)	0.192 (0.02)	0.167 (0.02)	↓13.02	<0.001	0.015/0.035
Flight time (s)	0.147 (0.02)	0.134 (0.01)	↓8.85	0.010	0.004/0.023
Step length (m)	1.55 (0.15)	1.61 (0.17)	↑3.87	0.001	-0.99/-0.03
Joint angles					
Initial contact					
θHip (º)	150.51 (6.0)	146.41 (4.51)	↓2.73	0.031	0.52/9.32
θKnee (º)	160.83 (6.04)	163.04 (5.12)	↑2.37	0.487	-4.31/2.16
θAnkle (º)	117.49 (6.25)	126.18 (8.19)	↑7.40	0.001	-11.94/-3.91
Midstance					
θHip (º)	155.75 (4.53)	155.44 (4.98)	↓0.99	0.597	-3.06/5.13
θKnee (º)	140.78 (5.58)	146.27 (5.49)	↑3.90	<0.001	-8.83/-4.11
θAnkle (º)	101.77 (5.11)	110.67 (6.74)	↑8.75	<0.001	-14.24/-7.40
Toe-off					
θHip (º)	161.20 (6.67)	193.13 (10.12)	↑19.81	<0.001	-41.22/-25.62
θKnee (º)	163.73 (6.22)	161.88 (5.20)	↓1.13	0.810	-3.99/3.18
θAnkle (º)	136.49 (6.39)	139.18 (5.96)	↑1.98	0.279	-5.68/1.81

%Δ: percentage of change between both values; ↓↑ indicates the direction of change when running velocity increases; CI: Confidence Interval; θ: joint angle

Table 4. Means (±SD) of kinematic variables during the first and last run of both high-intensity intermittent training protocols (10x400m vs. 40x100m)

Variables	10x400m protocol		*p-value*	95% CI	40x100m protocol		*p-value*	95% CI
	1st run	10th run			1st run	40th run		
Initial contact								
θHip (º)	150.51 (6.0)	151.54 (6.33)	0.341	-3.31/1.24	146.41 (4.51)	145.56 (5.83)	0.620	-2.72/4.40
θKnee (º)	160.83 (6.04)	156.86 (9.37)	0.066	-0.32/8.26	163.04 (5.12)	160.16 (5.71)	0.067	-0.22/5.97
θAnkle (º)	117.49 (6.25)	117.73 (5.79)	0.847	-3.02/2.53	126.18 (8.19)	125.46 (6.69)	0.756	-4.24/5.68
Midstance								
θHip (º)	155.75 (4.53)	156.72 (5.7)	0.166	-2.39/0.46	155.44 (4.98)	153.56 (7.27)	0.283	-1.71/5.46
θKnee (º)	140.78 (5.58)	140.38 (6.05)	0.759	-2.41/3.22	146.27 (5.49)	145.64 (6.02)	0.668	-2.45/3.71
θAnkle (º)	101.77 (5.11)	101.44 (6.79)	0.813	-2.77/3.44	110.67 (6.74)	112.03 (6.18)	0.487	-5.58/2.85
Toe-off								
θHip (º)	161.20 (6.67)	161.29 (6.23)	0.868	-1.33/1.13	193.13 (10.12)	195.82 (6.25)	0.324	-8.30/2.92
θKnee (º)	163.73 (6.22)	163.64 (5.94)	0.941	-2.54/2.73	161.88 (5.20)	159.58 (4.36)	0.106	-0.55/5.17
θAnkle (º)	136.49 (6.39)	137.80 (6.75)	0.613	-6.87/4.26	139.18 (5.96)	139.13 (5.78)	0.977	-3.66/3.77

CI: Confidence Interval; θ: joint angle

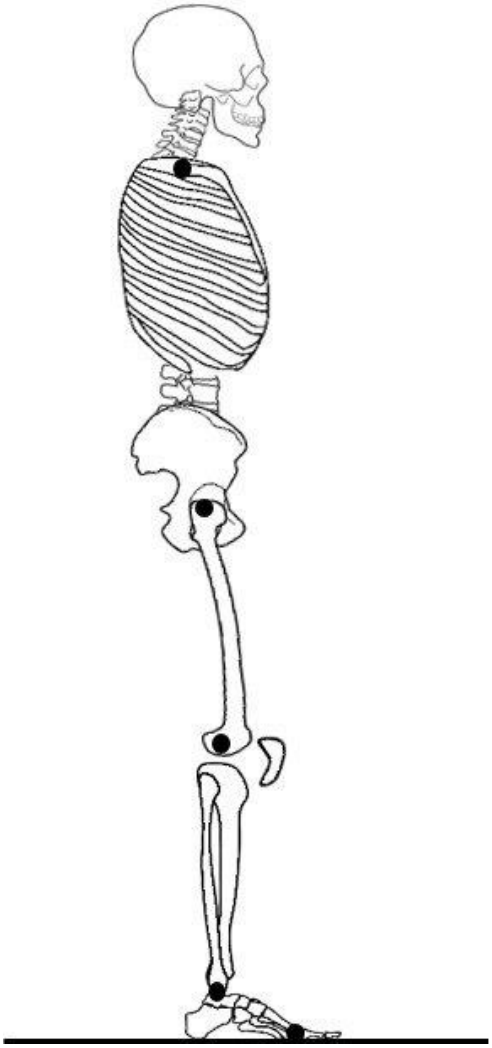

Figure 1. Landmarks placement. 1: acromion; 2: greater trochanter; 3: lateral epicondyle of the femur; 4: lateral malleolus; 5: fifth metatarsal

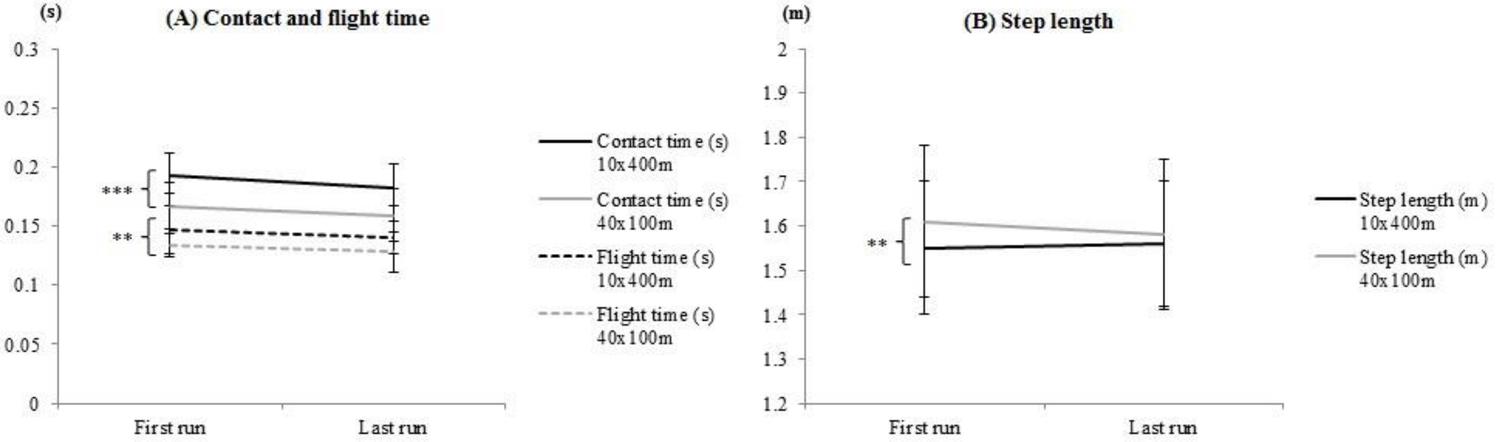

Figure 2. Spatial-temporal parameters during both HIIT protocols (10x400m vs. 40x100m) at first and last run of each one. (A) Contact time and flight time; (B) Step length. * indicates significant differences between-groups at first run (** p≤0.01; *** p≤0.001)

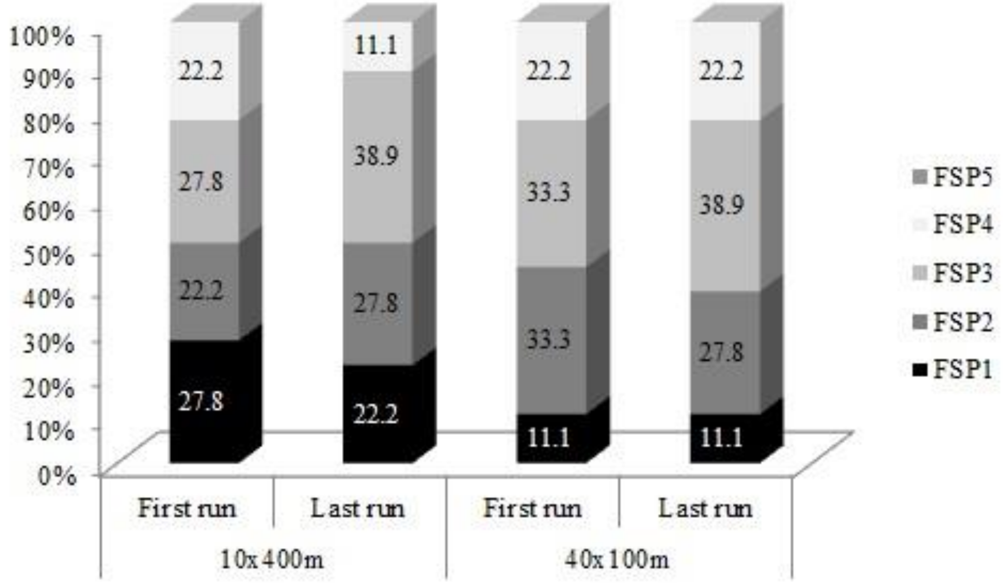

Figure 3. Foot strike pattern (FSP) and changes induced over two different HIIT protocols (10x400m vs. 40x100m). FSP1: high-rearfoot strike; FSP2: rearfoot strike; FSP3: midfoot; FSP4: forefoot strike; FSP5: high-forefoot strike

4. A HIGH-INTENSITY INTERMITTENT TRAINING-BASED TRAINING PROGRAMME FOR ENDURANCE ATHLETES

(PAPERS VIII AND IX)

A high-intensity intermittent training-based running programme allows triathletes to reduce weekly running distances without impairing muscular performance and body composition

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Submitted

TITLE: A HIGH-INTENSITY INTERMITTENT-BASED RUNNING PROGRAMME ALLOWS TRIATHLETES TO REDUCE WEEKLY RUNNING DISTANCES WITHOUT IMPAIRING MUSCULAR PERFORMANCE AND BODY COMPOSITION

RUNNING HEAD: HIIT AND ENDURANCE ATHLETES

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ABSTRACT

Background: Extensive evidence supports the benefits of high-intensity intermittent training (HIIT) for endurance athletes. Additionally, the importance of neuromuscular characteristics and body composition in determining running economy and, thereby running performance, have been widely documented. However, previous studies performing HIIT interventions have been conducted in single sports, such as swimming, running or cycling, but no previous work has proposed any strategy to insert and apply the HIIT methodology to a triathlon.

Aim: This study aimed to determine the effect of a 5-week HIIT-based running programme on body composition and muscular performance parameters in triathletes.

Methods: Thirteen triathletes were matched into two groups, experimental group (EG) and control group (CG). The CG was asked to maintain their training routines, whilst the EG modified their running plans (HIIT-based) but maintained their swimming and cycling routines. Body composition, vertical jump, stretch-shortening cycle utilization (SSC) and sprint ability were performed before (pretest) and after (posttest) the intervention period.

Results: No significant differences between groups were found at pretest. At posttest, the EG obtained higher values in countermovement jump ($p = 0.005$, ES > 0.7) and SSC ($p = 0.017$, ES > 0.7), with lower times ($p = 0.001$, ES > 0.7) in sprint. Body composition parameters remained unchanged in both groups ($p \geq 0.05$, ES < 0.4).

Conclusion: The results showed that a HIIT-based running plan induced improvements superior to the plan performed by the CG, in jumping, sprinting ability and SSC, without impairing body composition parameters. Thus, this study highlight the effectiveness of this HIIT-based training programme for improving explosive muscular power and the rebound capabilities of the athletes.

Keywords: endurance athletes; interval training; reactive strength; training prescription

1. INTRODUCTION

Over the last 30 years, the popularity of triathlon has increased tremendously and this fact has been accompanied by an increase in the number of athletes sustaining injuries (1). Studies investigating factors relating to levels of training that contributed to injury, identified that training for or competing in the running component of the triathlon resulted in the greatest number of injuries (1,2). The literature suggests a linear relationship between training patterns and injury occurrence. Risk of injury increased with increased weekly training distances, especially for running (1,2). Likewise, a growing body of literature highlights the role of mean training intensity over a season in optimising athletic performance (3–7).

Although there is no universal definition, high-intensity intermittent training (HIIT) generally refers to repeated short to long bouts of high-intensity exercise – performed at close to 100% maximal oxygen uptake (VO_{2max}) – interspersed with recovery periods. As a training method that leads to a reduction in weekly running distances and an increase in mean running intensity without impairing athletic performance, it is considered one of the most effective forms of exercise for improving the physical performance of athletes (3–7). Extensive evidence supports the benefits of fast intermittent exercises for endurance runners (8–15). Previous studies performing HIIT interventions have been conducted in single sports, such as swimming (16), running (8,12,17) or cycling (18), but no previous work has proposed any strategy to insert and apply the HIIT methodology to a triathlon.

In recent years, evaluation of neuromuscular parameters has become an important consideration for endurance athletes and coaches. Whilst jumping tests are commonly used to assess both the acute effects of workouts at the neuromuscular level (19–21) and the effectiveness of training protocols on lower body power (22,23), parameters related with stretch-shortening cycle utilization (SSC), have been used for monitoring training adaptations over a sports season (24) and have been associated with performance enhancement, injury prevention and fatigue mechanisms (25).

It is well established the importance of neuromuscular characteristics in determining running economy and, thereby, running performance (22,26). Whilst, the precise mechanisms by which HIIT can improve endurance performance remain undetermined, potential adaptations that may contribute to the improvement in endurance performance following HIIT include the ability of skeletal muscle to buffer hydrogen ions (27), as well as increases in Na+/K+ pump capacity (8), anaerobic capacity (18) and/or motor unit activation (17,28).

Likewise, it is widely accepted the influence of body mass and nutritional status on running economy and, thereby, running performance (29). A systematic review about HIIT and fat loss (30) recognised the potential of this training method as an effective protocol for reducing fat of overweight individuals. However, according to trained populations, more research is clearly needed and coaches are still wondering whether a higher intensity allows HIIT to compensate for the reduced total volume in terms of total energy expenditure and, therefore, whether an important reduction in training volume will lead to changes in body composition parameters despite a higher training intensity or not.

This study aimed to determine the effect of a 5-week HIIT-based running programme on body composition, and muscular performance parameters in triathletes. Even though all triathlons (from ironman- to sprint-distance) are considered continuous endurance events (31), the benefits reported by previous studies performing HIIT interventions with endurance athletes (8–15) allow the authors to hypothesize that, despite an important reduction in weekly running distance and the short duration of the training programme, a HIIT-based running plan would induce superior improvements in jumping ability, sprinting ability and (SSC) without impairing body composition parameters.

2. MATERIALS AND METHODS

2.1. Subjects

Sixteen male triathletes (aged= 33 ± 5 years, body mass= 74 ± 5 kg, stature= 176 ± 9 cm) volunteered for the study, which was performed according to the ethical standards established by the Helsinki Declaration of 1975 and was approved by the local ethical committee of the University of Jaen (Spain). Inclusion criteria were: (i) older than 18; (ii) actively competing in races; (iii) no history of injury in the 6 months before the study; and, (iv) not engaged in a high-intensity training programme. Three of the triathletes did not complete the study because of illness during the intervention period, and their data are excluded. Each signed a written informed consent before participation and completed a detailed questionnaire, recorded race distances and times, training type, total distance and training duration, which were confirmed by their respective coaches. The group competed in a sprint-distance triathlon race to validate the current performance status. Further information about participants – demographic and training background - is shown in Table 1.

TABLE 1 ABOUT HERE

2.2. Experimental design

The study was conducted between March and April 2015. At the time of these observations, the triathletes had completed between 3 and 4 months of training. A parallel two-group, longitudinal (pre, post) design was used. Thus, physical tests were performed before (pre-intervention) and after (post-intervention) the 5-week intervention period. The triathletes were assigned and matched to two groups, an experimental group (EG) and a control group (CG), based on their performance in a sprint-distance triathlon competition (overall race time). In order to investigate the effect of a HIIT-based running programme, triathletes from the CG were asked to maintain their training routines, whilst triathletes from the EG modified their running plans, but their swimming and cycling routines remained unchanged. Therefore, during the HIIT period, the CG kept performing continuous moderate-intensity training sessions (for swimming, cycling and running), whilst the EG implemented their continuous moderate-intensity sessions for swimming and cycling, with HIIT for running.

2.3. Training

All training sessions performed within this training programme have been investigated in previous studies on endurance athletes (7,8,19) and training volume and intensity were prescribed according to these works. Instructions for athletes regarding exercise intensity were given according to running pace, in terms of kmh. For this purpose, the variable used was the velocity associated with VO_{2max} (VV_{O2max}) - indirectly calculated through the velocity of a 3000 m race (32,33), information reported by the coaches.

The HIIT programme included 3-4 running sessions per week for 5 weeks. This running programme led to an important reduction of average weekly running distance in the EG (-69.8%, from 33.6 km/week before training programme to 10.14 km/week during the plan). A description of the 5-week HIIT-based programme is reported in Table 2. As for the swimming and cycling routines, the athletes from EG kept performing the same training programme (~3-4 hour/week spread over ~2-3 session/week for swimming, and ~6-8 hour/week over ~3-4 session/week for cycling).

TABLE 2 ABOUT HERE

2.4. Materials and testing

The triathletes were instructed to refrain from intense exercise 2 days preceding testing and to perform the last HIIT session 3 days before the post-test. They were not allowed to eat during the hour preceding the test or to consume coffee or other products containing caffeine during the preceding 3 h. Pre- and post-testing was conducted at the same time of day to avoid the influence of the circadian rhythm, and under similar environmental conditions (20-24ºC). Body composition, vertical jump, SSC, and sprint ability were assessed in both testing sessions:

Body composition analysis: This was performed at the beginning of the testing session. A stadiometer (Seca 222, Hamburg, Germany) was used for determining the height of the participants, whilst a portable eight-polar tactile-electrode impedanciometer (InBody R20; Biospace, Seoul, Korea) to measure body mass (kg) and other parameters, such as skeletal muscle mass (SMM) and body fat (%). This device has been previously validated (34).

Vertical jumping test: After body composition analysis, a standardised warm-up was performed. Then, countermovement jumps (CMJ) and squat jumps (SJ) were performed. The participants were experienced athletes who performed these tests in their daily training sessions. Moreover, to make sure the execution was correct, a familiarization session was carried out beforehand. The CMJ and SJ were recorded using the OptoGait system (Microgate, Bolzano, Italy). This technology has been declared as legitimate for field-based assessments of vertical jump height (35). Subjects performed two trials with a 15-second recovery period between them, and the best trial was used for the subsequent statistical analysis.

Both CMJ and SJ tests are commonly used to discriminate between the effects of the SSC in various athletic populations (36). Researchers have measured SSC performance from CMJ and SJ jump heights as an augmentation of a prior stretch (24). Pre-stretch augmentation (PSA) can be calculated as a percentage, with $PSA (\%) = [(CMJ - SJ) \times SJ^{-1}] \times 100$. This is considered to be a measure of the ability to utilize the muscle pre-stretching during the CMJ (24).

Sprinting test: A maximal 20 m linear sprint test (S20m) was performed after the jumping test. The triathletes performed this sprint test on the outdoor track and it was measured using two double-light barriers (Witty; Microgate Srl, Bolzano, Italy; accuracy of 0.001 s). Participants were instructed to start from the starting line and to run as fast as possible over the 20 m distance.

Post-pre differences (increase, Δ) were calculated for all of these tests (body composition parameters, CMJ, SJ, PSA, S20m) and used for the subsequent analysis.

2.5. Statistical Analysis

Descriptive statistics are represented as mean (*SD*). Tests of normal distribution and homogeneity (Kolmogorov-Smirnov and Levene's, respectively) were conducted on all data before analysis. Increase (Δ) of each variable as post-pre comparison was calculated and expressed as percentages (Δ%) and absolute values. The Wilcoxon test was used for determining within-group differences as a repeated measures analysis (pre-post). The magnitude of the differences between values were also interpreted using the *Cohen´s d* effect size (ES) (37). Effect sizes of less than 0.4 represented a small magnitude of change while 0.41–0.7 and greater than 0.7 represented moderate and large magnitudes of change, respectively (37). Additionally, between groups comparisons were done at pretest, at posttest, and with post-pre differences (Δ) in order to compare both the CG and EG and to find differences between them. For this purpose, the Mann-Whitney U test was used. The level of significance was $p < 0.05$. Data analysis was performed using SPSS (version 21, SPSS Inc., Chicago, Ill).

3. RESULTS

From the comparative analysis between CG and EG before the training programme (at pretest), no significant differences ($p \geq 0.05$) were found in demographic data, nor in body composition parameters. As for the characteristics of training routines and athletic level, the results obtained in both the CG and EG were similar, with no significant differences ($p \geq 0.05$) (Table 1).

The results obtained regarding the effect of the training programme on body composition parameters are presented in Table 3. No significant differences ($p \geq 0.05$, ES < 0.4) were found in CG nor EG, in any of the controlled variables (body mass, body fat and SMM). As for the post-pre difference (Δ), no significant differences between the CG and EG were found ($p \geq 0.05$).

TABLE 3 ABOUT HERE

The effect of the training programme on vertical jump ability and SSC utilization is shown in Figure 1. The EG significantly improved CMJ ($p = 0.018$, ES > 0.8, Δ% = 9.21%), and SJ performance ($p = 0.018$, ES > 0.8, Δ% = 5.98%), whilst CG remained unchanged ($p = 0.075$ and 0.197, ES < 0.4 in both, Δ% = -3.2% and -1.8%, respectively). As for the PSA, the triathletes from EG this was significantly increased ($p = 0.028$, ES > 0.8, Δ% = 5.04%) while no changes were observed for the CG ($p = 0.686$,ES < 0.4, Δ% = -0.25%). Regarding the between-groups comparison, no significant differences were found at pretest ($p \geq 0.05$). At posttest, values obtained in the EG were significantly higher in CMJ ($p = 0.005$) and in PSA ($p = 0.017$) than those in CG. Data from post-pre difference showed significant differences between the CG and EG in CMJ ($p = 0.001$), SJ ($p = 0.003$) and PSA ($p = 0.017$).

FIGURE 1 ABOUT HERE

As for sprinting ability (Figure 2), the EG improved its performance (-0.18s, Δ% = 7.21%, p = 0.018, ES > 0.8) whilst the CG impaired it (+0.14s, Δ% = 3.04%, p = 0.027, moderate ES). The between-groups comparison showed similar values at pretest for the CG and EG ($p \geq 0.05$), and significant differences at posttest –lower times in the EG than in the CG (p = 0.001). Post-pre difference also showed significant differences between the CG and EG (p = 0.001).

FIGURE 2 ABOUT HERE

4. DISCUSSION

The results obtained in this study confirmed the initial hypothesis: a low-volume HIIT-based running plan induced superior improvements in jumping ability, sprinting ability and stretch-shortening cycle utilization (SSC) to those of the running plan performed by the CG –based on higher volumes and lower intensities- without impairing body composition parameters. This running programme led to a huge reduction of average weekly running distance in the EG (-69.8%, from 33.6 km/week before the training programme to 10.14 km/week during the plan), as well as an increase in average running pace (participants did not include HIIT sessions in their training routines before this training programme so, an increase in running pace is supposed during this intervention). Taken together, this HIIT-based running plan combined with the already high training volumes of these triathletes in swimming and cycling, seems to be a more efficient training programme for improving muscular performance parameters of triathletes than the typically performed high-volume and low/moderate-intensity, as well as being an enough stimulus to maintain constant body composition parameters. Considering the link between high mileage and risk of injury (1,2) on the one hand, and between average training intensity and running performance (3–7) on the other hand, this training programme might be very useful, in terms of training prescription.

The HIIT protocol is well documented and various types of HIIT programmes have been shown to improve endurance performance and associated physiological variables (8–15). Nevertheless, as far as the authors know, previous studies performing HIIT interventions have been conducted in single sports, such as swimming, running or cycling, but no previous work has proposed any strategy to insert and apply the HIIT methodology to a triathlon. Moreover, most studies focused on HIIT-based running plans for endurance athletes assessed changes in athletic performance and physiological parameters, whilst there are only limited data available on neuromuscular adaptations and body composition changes in athletes subjected to HIIT interventions.

Neuromuscular characteristics have been suggested to play a critical role in the performance of endurance runners (22,26) and, in this regard, some studies have reported interesting adaptations after HIIT intervention. Interval training, by affecting glycolytic capacity, may lead to increased mitochondrial activity in type II fibers and thus show characteristics similar to those of type I fibers (38). Moreover, training at maximal and near-maximal exercise intensities seems to be effective in creating muscular adaptations such as improved buffering capacity (27), increased LDH activity (17) or increased activity of oxidative enzymes and expression of Na+-K+ pump subunits and lactate and H+ transporters (8,10). Nevertheless, the exact mechanism by which muscular performance improves after a period of HIIT in trained athletes is still unknown. What is clear is that a faster running pace during the HIIT sessions will demand higher levels of neural drive, will lead to higher levels of activation of the anaerobic glycolysis, and will recruit additional fast-twitch motor units for relatively short durations (39), and that rationale might be the physiological basis of the muscular improvement reported in the current study.

The results obtained in the current study showed that a 5-week HIIT-based running plan improved vertical jumping capacity (+9.21% in CMJ, and +5.98% in SJ), SSC utilization (+5.04% in PAS), and sprint ability (+7.21% in S20m) in triathletes, whilst triathletes from the CG who kept training at low-moderate intensity with high volumes did not experience changes in muscular performance variables. Despite some HIIT-based training programmes have been conducted with endurance runners (8–15), any of them assessed the changes induced in muscular performance parameters using sport-and training-specific tasks such as jumping and sprinting (field-based measurements), and that is why the comparison of the results obtained is difficult. If other sport modalities are considered, some previous studies have examined the effectiveness of HIIT- or SIT-based training programmes on muscular performance parameters in intermittent sports such as football (40) or tennis (41), and no changes were reported in jumping and sprinting abilities. Because of the demands of those sports, the initial muscular performance (baseline level) was already high so, this might be the explanation for the lack of improvements and, thereby, the differences in the results with our study.

Concerning the sprint ability, it is not usually tested in studies in which endurance athletes participate. However, sprint ability plays a key role in many endurance races of different sports modalities, by allowing athletes to unbalance a race in the last metres. In fact, some previous studies with endurance athletes (22,42) have observed a relationship between 20m sprinting velocity and the capability of the runner to produce power above VO_{2max}, and thus distance running performance. In this study, a low-volume HIIT-based running programme improved sprinting performance in comparison to a high-volume low/moderate intensity programme. This finding is consistent with suggestions made by previous authors (43), which explain that an enhanced sprint power following HIIT was expected, given that high-intensity training increases enzymatic activity related to anaerobic metabolism. However, to the best of the researchers´ knowledge, this is the first study checking the effect of replacing the usual training of endurance athletes with HIIT on sprint tests performed on the field.

Regarding the second question, the body composition changes in trained athletes subjected to HIIT interventions, the main finding of this study was that, despite a huge reduction in weekly running volume in the EG, body composition parameters were not impaired according to baseline values and to the CG, who maintained high training volumes. These results are in accord with previous studies (30,44,45). In fact, accumulating evidence suggests that HIIT has the potential to be an economical and effective exercise protocol for reducing fat of overweight individuals (30). Possible mechanisms underlying the HIIT-induced fat loss effect include increased exercise and post-exercise fat oxidation and decreased post-exercise appetite (30). Burgomaster et al. (44) showed that six sessions of HIIT had marked increases in whole body and skeletal muscle capacity for fatty acid oxidation. With endurance runners, Hernandez-Torres et al. (45) compared two single exercise sessions of the same duration (90 min) and distance (14 km): a continuous moderate-intensity training sessions vs. HIIT session, and the authors found that energy expenditure was higher during HIIT. Nevertheless, coaches are still wondering whether, in trained populations, a higher intensity allows HIIT to compensate for the reduced total volume in terms of total energy expenditure and, therefore, whether an important reduction in training volume will lead to changes in body composition parameters despite a higher training intensity or not. In this case, these data should be cautiously interpreted (due to the short length of the intervention period and the sensitivity of the measurement), and more studies examining the effects of HIIT on the body composition of athletic populations are clearly needed.

Finally, some limitations need to be considered. First, the duration of the intervention: most HIIT studies have investigated interventions lasting 2-to-10 weeks and it is not known whether HIIT at the expense of training volume continues to induce beneficial adaptations if the intervention period is prolonged. Second, the sample size: even conducting a non-parametric statistical analysis and calculating effect sizes, the small sample size must be taken into consideration. Notwithstanding these limitations, the current study offers some insight into training methods prescription for triathletes by determining the effectiveness of a HIIT-based running programme, which not only causes improvements in muscular performance parameters and allows athletes to maintain body composition, but also facilitates the reduction of a major risk factor for injury in triathletes such as weekly running distances.

5. CONCLUSION

The current study showed that a low-volume HIIT-based running plan combined with the already high training volumes of these triathletes in swimming and cycling, induced superior improvements in jumping ability, sprinting ability and SSC than the typically performed high-volume and low/moderate-intensity. Additionally, the reduction of the weekly running distances did not impair body composition parameters.

Therefore, from a practical point of view, the improvements reported by this study highlight the effectiveness of this HIIT-based training programme for improving explosive muscular power and the rebound capabilities of the athletes -critical factors in both running performance and injury prevention- without impairing body composition –closely related to work economy.

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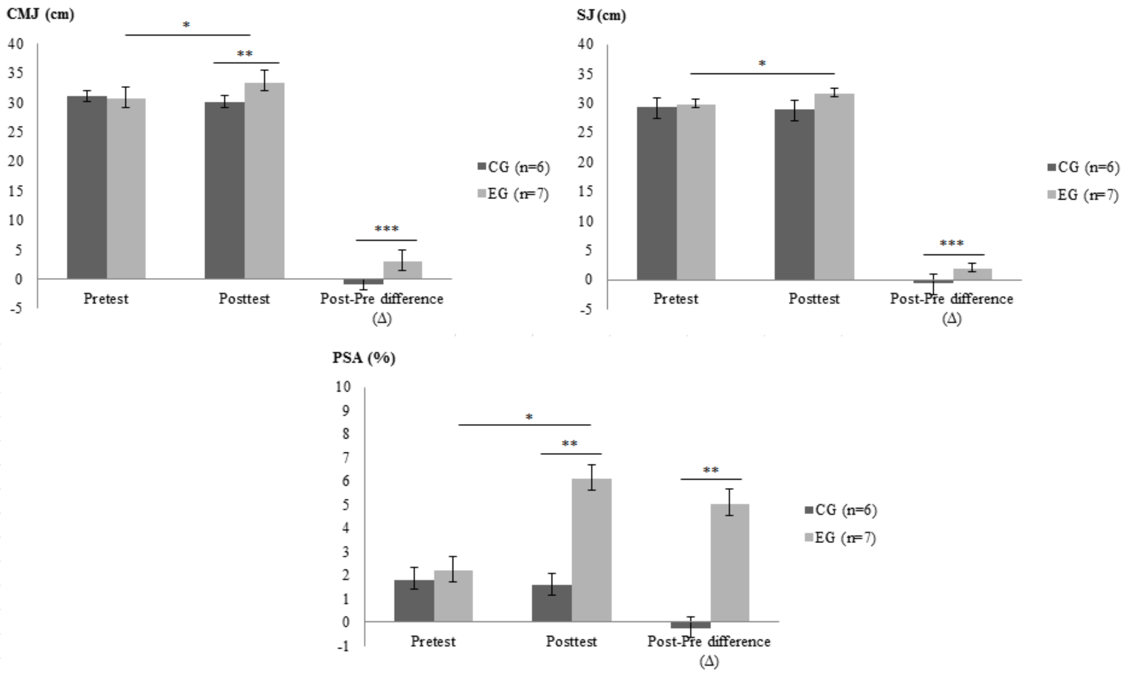

Figure 1. Muscular performance parameters before (pretest) and after (posttest) the intervention period: a comparison within- and between groups. CG: control group; EG: experimental group; CMJ: countermovement jump; SJ: squat jump; PSA: pre-stretch augmentation (%). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

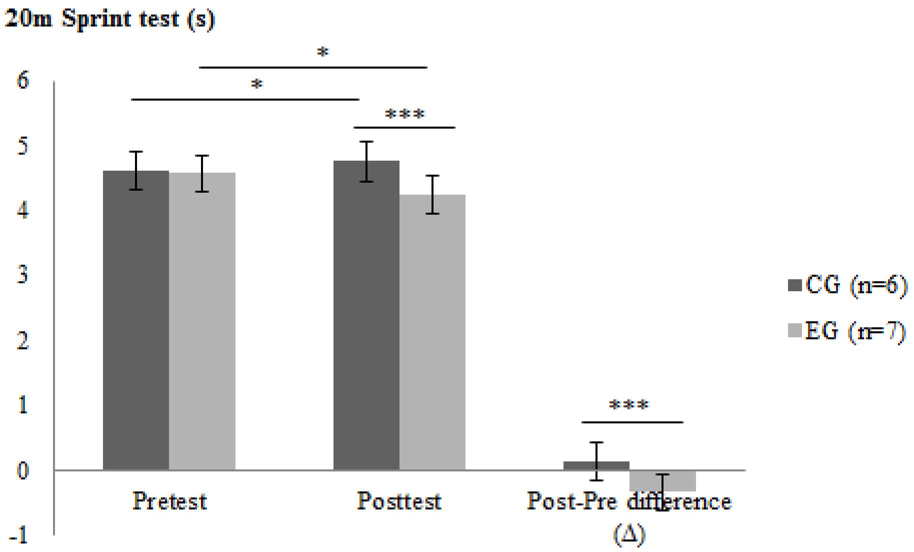

Figure 2. Results obtained in a maximal 20 m linear sprint test (S20m) before and after HIIT-based training programme for both control and experimental groups (CG and EG, respectively). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Table 1. Demographic and anthropometric data of the participants (mean, SD), as well as information about characteristics of their training routines and athletic performance.

Variables	Whole-group (n=13)	Control Group (n=6)	Experimental Group (n=7)	*p-value*
Age (years)	33.77 (5.42)	31.83 (3.18)	35.40 (6.50)	0.181
Body mass (kg)	74.33 (5.76)	74.33 (7.19)	74.32 (5.56)	0.945
Height (m)	1.76 (0.09)	1.75 (0.07)	1.77 (0.06)	0.415
Training volume (h/wk)	15.88 (2.39)	15.17 (2.48)	16.50 (2.32)	0.339
Number of workouts (s/wk)	9.77 (1.43)	9.83 (1.6)	9.71 (1.48)	0.888
Swimming sessions (s/wk)	2.74 (0.7)	2.71 (0.52)	2.66 (0.44)	0.766
Cycling sessions (s/wk)	3.69 (0.81)	3.81 (0.67)	3.60 (0.49)	0.590
Running sessions (s/wk)	3.46 (0.77)	3.33 (0.81)	3.57 (0.78)	0.654
Swimming volume (km/wk)	7.92 (2.21)	8.20 (1.71)	7.61 (2.2)	0.481
Cycling volume (km/wk)	176.30 (31.7)	180.12 (22.1)	173.98 (30.5)	0.211
Running volume (km/wk)	31.92 (8.3)	30 (7.75)	33.57 (8.9)	0.463
Swimming volume (h/wk)	3.66 (0.7)	3.82 (0.61)	3.51 (0.49)	0.398
Cycling volume (h/wk)	7.19 (1.25)	7.44 (1.39)	7.09 (1.1)	0.606
Running volume (h/wk)	4.79 (1.29)	4.25 (1.00)	5.05 (1.26)	0.242
Overall race time (min)	64.98 (6.57)	65.21 (6.69)	64.98 (6.98)	0.912

h/wk: hours per week; s/wk: sessions per week; km/wk: kilometres per week

Table 2. Detailed description of the 5-week HIIT-based running programme, including exercises, intensity prescribed and training volume.

Exercise	**Intensity (%VVO$_{2max}$)**	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**
100-m runs with 30-s rest	120-130%	x20	x25	x30	x35	x20
400-m runs with 90-s rest between runs and 3-min between sets	105-110%	2x (4x400m)	2x (5x400m)	2x (5x400m)	2x (5x400m)	2x (3x400m)
Bouts of 120-s runs with 120-s rest	100-105%	x7	x7	x7	x7	--
30-s all-out running sprints with 3-min rest	All-out	--	--	x4	x6	x6
Training volume	session/week	3	3	4	4	3
	km/week	~9.4	~10.7	~11.9	~13.0	~5.7

~ means that training volume in terms of km per week might vary according to the metres covered in some exercises

Table 3. Body composition parameters before (pretest) and after (posttest) training programme in both the control (CG) and experimental group (EG).

Variables		CG (n= 6)	EG (n= 7)	*p-value §*
Body mass (kg)	Pretest	74.33 (7.19)	74.32 (5.56)	0.945
	Posttest	74.87 (7.67)	74.12 (5.01)	0.857
	Post-Pre difference (Δ, %)	0.54 (0.73%)	-0.20 (0.27%)	0.571
	p-value ^	0.285*	0.188*	
Body fat (%)	Pretest	15.55 (5.41)	11.49 (2.59)	0.098
	Posttest	16.43 (4.94)	12.58 (3.05)	0.252
	Post-Pre difference (Δ, %)	0.88 (5.66%)	1.09 (9.49%)	0.836
	p-value ^	0.828*	0.406*	
Skeletal muscle mass (kg)	Pretest	35.62 (3.36)	37.67 (2.12)	0.181
	Posttest	35.60 (1.60)	37.00 (1.74)	0.393
	Post-Pre difference (Δ, %)	-0.02 (0.06%)	0.67 (1.77%)	0.571
	p-value ^	0.593*	0.142*	

§ determines between-groups differences (p<0.05, Mann Witney U-test); ^ determines within-group differences (p<0.05, Wilcoxon test); * indicates the *Cohen´s d* effect size (* small, ES < 0.4; ** medium, ES 0.4-0.7; *** large, ES > 0.7); Δ: change, in absolute values; %: percentage of change

A HIIT-based running plan improves athletic performance by improving muscle power

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Submitted

A HIIT-based running plan improves athletic performance by improving muscle power

Running head: HIIT for endurance athletes

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ABSTRACT

This study aimed to examine the effect of a five-week HIIT-based running plan on athletic performance, and to compare the physiological and neuromuscular responses during a sprint-distance triathlon before and after the HIIT period. Thirteen triathletes were matched into two groups: the experimental group (EG) and the control group (CG). The CG was asked to maintain their normal training routines while the EG maintained only their swimming and cycling routines and modified their running routine. Participants completed a sprint-distance triathlon before (pre-test) and after (post-test) the intervention period. In both pre- and post-tests, the participants performed four jumping tests: before the race (baseline), post-swim, post-cycling, and post-run. Additionally, heart rate was monitored (HRmean) while RPE and blood lactate accumulation (BLa) were registered after the race. No significant differences ($P \geq 0.05$) between groups were found at pre-test. After the intervention period, the EG significantly improved jumping performance (~5-8%, $P=0.05$), cycling performance ($P=0.046$) and running time ($P=0.018$) during the competition. The CG remained unchanged ($P \geq 0.05$). No changes ($P \geq 0.05$) were observed in RPE, HRmean and BLa. A linear regression analysis showed that ΔCMJ predicted both the ΔRu_time ($R^2=0.559$; $P=0.008$) and the ΔOverall_time ($R^2=0.391$; $P=0.048$). This low-volume, HIIT-based running plan combined with the high training volumes of these triathletes in swimming and cycling improved athletic performance during a sprint-distance triathlon. This improvement may be due to improved neuromuscular characteristics that were transferred into improved muscle power and work economy.

Keywords: endurance athletes; interval training; muscular performance parameters; training prescription

INTRODUCTION

Increased participation in recreational and competitive triathlons over the last decade has been accompanied by an increase in the number of athletes sustaining injuries (10). Studies investigating factors relating to levels of training that contribute to injury identified that training for or competing in the running component of the triathlon resulted in the greatest number of, and often the most severe, injuries (10,29). Specifically, risk of injury increased with increased weekly training distances, especially for running (10,29). In contrast, a growing body of literature points to mean training intensity over a season as the key factor for performance improvement (2,9,21). A clear example for endurance sports was reported by Billat et al. (5) who showed that male Kenyan runners training at higher speeds had a significantly better 10km performance than Kenyan athletes training at lower speeds, despite the elite status of both groups.

As a training method that leads to a reduction in weekly running distances and an increase in mean running intensity without impairing athletic performance, high-intensity intermittent training (HIIT) is considered one of the most effective forms of exercise for improving the physical performance of athletes (3,4,8,9,21). Although there is no universal definition, HIIT generally refers to repeated short to long bouts of high-intensity exercise – performed at close to 100% maximal oxygen uptake (VO_{2max}) – interspersed with recovery periods.

The HIIT protocol is well documented (2,9), and various types of HIIT programmes have been shown to improve endurance performance in runners (1,13,18) and cyclists (11,20). However, despite the reported benefits of training at a high intensity, endurance athletes continue to train mostly at low intensities (14); thus, more evidence is needed to “convince” coaches and athletes of the importance of HIIT for endurance performance. Finally, all of these studies have been performed in a single sport, by replacing a part of their training programmes and reducing, in a variable percentage (0-50%), the average training distance. Nevertheless, to date, no previous studies have proposed any strategy to insert and apply the HIIT methodology to a triathlon.

Taken together, the aim of this study was to examine the effect of a five-week HIIT-based running plan on the athletic performance of triathletes, and to compare the physiological and neuromuscular responses during a sprint-distance triathlon race before and after this high-intensity and low-volume intervention period. The authors hypothesise that a low-volume HIIT-based running plan, combined with the already high training volumes of these triathletes in swimming and cycling, might be a more efficient training programme for improving the performance of triathletes than the typically performed high-volume and low/moderate-intensity exercise.

METHODS

Experimental Approach to the Problem

This study analyses the effect of incorporating HIIT on muscle power measurement and simulated sprint triathlon performance. Using a between-group design (experimental group [EG] and control group [CG]), 13 triathletes were assessed.

Subjects

Sixteen male triathletes (aged= 33 ± 5 years, body mass= 74 ± 5 kg, height= 176 ± 9 cm) volunteered for the study, which was performed according to the ethical standards established by the Helsinki Declaration of 1975 and was approved by the local ethical committee of the University of Jaen (Spain). Inclusion criteria were: (i) older than 18; (ii) actively competing in races; (iii) a clean bill of health for the past 6 months; and, (iv) not engaged in a high-intensity training programme. Three of the triathletes did not complete the study because of illness during the intervention period, and their data were excluded. Each signed a written informed consent before participation, completed a detailed questionnaire, and recorded race distances and times, training type, total distance and training duration, which were confirmed by their respective coaches. The group competed in a sprint-distance triathlon race to validate the current performance status. Further information about participants – demographic and training background - is shown in Table 1.

TABLE 1 ABOUT HERE

Experimental design

The study was conducted between March and April 2015. At the time of these observations, the triathletes had completed between 3 and 4 months of training. A parallel two-group, longitudinal (pre, post) design was used. Thus, physical tests were performed before (pre-test) and after (post-test) the 5-week intervention period. The triathletes were assigned and matched to two groups, EG and CG, based on their performance in a sprint-distance triathlon competition (overall race time). In order to investigate the effect of a HIIT-based running programme, triathletes from the CG were asked to maintain their training routines, whilst triathletes from the EG modified their running plans, but maintained their swimming and cycling routines. Therefore, during the HIIT period, the CG performed continuous moderate-intensity training sessions (for swimming, cycling and running), whilst the EG implemented their continuous moderate-intensity sessions for swimming and cycling and HIIT for running.

Training

All HIIT sessions performed within this training programme have been investigated in previous studies on endurance athletes (1,9,31) and training volume and intensity were prescribed according to these works. Instructions for athletes regarding exercise intensity were given according to running pace, in terms of kmh. For this purpose, the variable used was the velocity associated with VO_{2max} (VV_{O2max}) which was indirectly estimated through the velocity of a 3000 m race (12,19), information reported by the coaches.

The HIIT programme included 3-4 sessions per week for 5 weeks. This running programme led to an important reduction of average weekly running distance in the EG (-69.8%, from 33.6 km/week before training programme to 10.14 km/week during training programme). A description of the 5-week HIIT-based programme is reported in Table 2.

TABLE 2 ABOUT HERE

Materials and Testing

The triathletes were instructed to refrain from intense exercise two days preceding testing and to perform the last HIIT session three days before the post-test. They were not allowed to eat during the hour preceding the test or to consume coffee or other products containing caffeine during the preceding three hours. Pre- and post-testing were conducted at the same time of day to avoid the influence of the circadian rhythm and under similar environmental conditions (20-24ºC).

Either at pre- or post-test, participation involved the execution of a sprint-distance triathlon race (750 m swimming, 20 km cycling and 5 km running), which was completely performed in simulated conditions, in the same sports facilities (closer than 100 meters to each other). The triathlon involved: swimming in an eight-lane, 25-m pool; cycling on their own road racing bicycles, connected to the same electromagnetically braked roller (Tacx Vortex T2170, Wassenaar, The Netherlands), which was calibrated to quantify and adjust wheel-ergometer rolling resistance to 1.1–1.6 kg, as prescribed by the manufacturer; and running on an outdoor 400-m synthetic track.

In both occasions (pre- and post-test), just before starting the race and after a standardised warm-up, the participants performed jumping tests (countermovement [CMJ] and squat jumps [SJ]) as baseline values. These measurements were repeated three more times, after swimming (Post-Sw), after cycling (Post-Cy), and after running (Post-Ru), in order to monitor the neuromuscular response during the competition. The participants were experienced athletes who performed jumping tests in their daily training sessions. Moreover, to make sure the execution was correct, a familiarisation session was carried out during the last training session before testing. The CMJ and SJ were recorded using the OptoGait system (Microgate, Bolzano, Italy), which has been previously used in similar studies (22). Subjects performed two trials with a 15-second recovery period between them, and the best trial was used for the statistical analysis.

The elapsed time (s) for the swimming, cycling and running stages, and overall triathlon (transition times excluded) were registered for the subsequent analysis. Participants were experienced triathletes who had competed in these events; thus, the only instructions were to finish the race as fast as they could (transitions included). No other guidelines were provided as to exercise intensity, apart from the participants being informed that they were to exercise at an intensity of their own choice.

Additionally, in order to control the exhaustion level after the race and possible adaptations to the training programme, some parameters were registered at both pre- and post-test: cardiovascular response - in terms of heart rate, in bpm - was monitored (Garmin Forerunner 405, KS, USA) throughout the race, and the average heart rate (HRmean) during every stage of the race was used for the analysis; the rating of perceived exertion (RPE) was recorded on the 6–20 Borg Scale (6) immediately after the race; and blood lactate accumulation (BLa), at 1-min after the race, was measured via fingertip blood samples, which were analysed with a portable lactate analyser (Scout Lactate, SensLab GmbH, Leipzig, Germany).

Statistical Analysis

Descriptive statistics are represented as mean (*SD*). Tests of normal distribution and homogeneity (Kolmogorov-Smirnov and Levene's) were conducted on all data before analysis. The Wilcoxon test was used for determining within-group differences as a repeated measures analysis. Additionally, between groups comparisons were done at pre-test in order to compare both the CG and EG. For this purpose, the Mann-Whitney U test was used. A Spearman correlation analysis was performed between the post-pre increase in elapsed time for swimming, cycling, running and overall triathlon (ΔSw_time, ΔCy_time, ΔRu_time and ΔOverall_time, respectively), with the post-pre increase in baseline CMJ and SJ values (ΔCMJ, ΔSJ). Based on the findings from the correlation analysis, a simple linear regression analysis was used to predict ΔRu_time and ΔOverall_time from the ΔCMJ during the intervention. The level of significance was $P<0.05$. The data analysis was performed using SPSS (version 21, SPSS Inc., Chicago, Ill).

RESULTS

In a comparison between the CG and EG before the training programme (pre-test), no significant differences ($P \geq 0.05$) were found in demographic data or in body composition parameters. As for the characteristics of training routines and athletic level, the results obtained in both the CG and EG were similar with no significant differences ($P \geq 0.05$) (Table 1).

The results obtained regarding the effect of the training programme on athletic performance are presented in Figure 1. At pre-test, both the CG and EG showed similar athletic levels with no significant differences in swimming ($P=0.731$), cycling ($P=0.836$) or running ($P=0.466$). After the intervention period, the EG significantly improved cycling time (3.85%, $P=0.046$) and 5 km running performance (3.93%, $P=0.018$), while the CG remained unchanged ($P \geq 0.05$).

FIGURE 1 ABOUT HERE

Cardiovascular response during every stage, and RPE and BLa after the race, are shown in Table 3. No significant differences ($P \geq 0.05$) between groups were found at pre-test. After the HIIT intervention, neither the CG nor the EG experienced significant alterations in any variable analysed ($P \geq 0.05$).

TABLE 3 ABOUT HERE

The neuromuscular response to a sprint-distance triathlon race, measured by means of vertical jump ability, and the effect of the five-week intervention period on this response are shown in Figure 2. No significant differences between the CG and EG were found at pre-test in baseline values (CMJ: 30.5 and 31.08 cm; SJ: 29.77 and 29.4 cm, for the EG and CG, respectively; $P \geq 0.05$). After the training programme, the EG experienced significant improvements in CMJ (+8.30%, $P=0.015$) and in SJ (+5.31%, $P=0.026$), while the CG experienced non-significant impairments in CMJ (-0.8%, $P=0.175$) and SJ (-4.93%, $P=0.075$). Concerning the dynamic of CMJ and SJ during the race, the repeated measures analysis showed no significant changes ($P \geq 0.05$) at pre or post-test for both the CG and EG.

FIGURE 2 ABOUT HERE

The Spearman correlation analysis showed significant correlations between ΔCMJ and ΔSJ with ΔRu_time ($P<0.001$), and between ΔCMJ and ΔOverall_time ($P=0.040$). A linear regression analysis showed that ΔCMJ predicted both the ΔRu_time (R=0.748; $R^2=0.559$; $P=0.008$) and the ΔOverall_time (R=0.625; $R^2=0.391$; $P=0.048$).

DISCUSSION

The major finding of the present study was that the inclusion of a HIIT-based running plan with a reduction in training volume not only resulted in improved muscular performance (~5-8% in vertical jump ability), but also increased athletic performance during a sprint-distance triathlon (improvements of 2.76% in swimming time, 3.85% in cycling time and 3.93% in running time). Conversely, the triathletes from the CG, who continued their usual high-volume and low/moderate-intensity training programme, did not experience significant changes in muscular performance parameters or racing times. Additionally, the improvements reported by the EG in athletic performance were not accompanied by significant changes in the physiological response during the simulated race or in exhaustion level reached, which indicates that the triathletes experienced some adaptations that allow them to race faster with the same physiological impact.

In order to justify this study, some facts must be considered. First, a growing body of literature points to mean training intensity over a season as the key factor for performance improvement (2,9,21). It is also known that the risk of injury increases with increased weekly running distances in triathletes (10,29). With regard to this, the current running programme led to a substantial reduction in average weekly running distance in the EG (-69.8%, from 33.6 km/week before the training programme to 10.14 km/week during the plan), as well as an increase in average running pace (participants did not include HIIT sessions in their training routines before this training programme).

Second, independent of the differences in distance and duration, all triathlons are considered continuous endurance events (30). Despite the physiological basis of aerobic endurance being not clearly understood (7), it is well known that some of the major physiological determinants of endurance performance are work economy, lactate threshold and maximal oxygen consumption (7). It has been shown that the presence of HIIT in endurance athletes´ training programmes facilitates the aforementioned adaptations (1,13,18,20). Likewise, the importance of high volumes performed at low/moderate-intensity for maximising athletic performance in endurance sports has also been demonstrated (23). For both reasons, a combination of high training volume at low exercise intensities and lower training volumes of HIIT seems to be necessary to obtain optimal development of endurance performance (2,8,9,21,28). In the current training programme, all of these suggestions have been taken into consideration by ensuring the presence of low/moderate-intensity over long periods of time (through swimming and cycling sessions) and by reducing weekly running volumes and increasing the average intensity of running sessions by means of HIIT.

Regarding the results obtained, this study is in agreement with previous works that have shown the effectiveness of HIIT programmes for improving endurance performance and associated physiological variables (1,11,13,18,20). Focusing on athletic performance of trained individuals, the finding of a ~3-4% improvement in swimming, cycling and running performance following HIIT intervention is similar to the findings of Laursen et al. (20), who reported a 4.4% improvement in a 40 km cycling time trial after HIIT. Likewise, previous works (1,13) have reported an improvement in 3 km and 10 km running performance (3 to 7%) in endurance runners after different HIIT programmes. To our knowledge, just one study (17) showed neither improvements nor decrements in athletic performance after a HIIT intervention in swimmers. As the authors explained, those results might be due to the extensive experience of the participants in HIIT exercises –criterion not met in the rest of studies. Previous studies performing HIIT interventions have been conducted in single sports, such as swimming (17), running (1,13,18) or cycling (20), but no previous work has proposed any strategy to insert and apply the HIIT methodology to a triathlon. In this regard, this study shows that the presence of HIIT in the triathletes´ running plan not only improves running performance, but also cycling performance during a sprint-distance competition, which might be associated with the "cross-training" principle (a phenomenon that refers to the cross-transfer of training effects from one sport to another (25).

The precise mechanisms by which HIIT can improve endurance performance remain undetermined. Potential adaptations that may contribute to the improvement in endurance performance following HIIT include the increased ability of skeletal muscle to buffer hydrogen ions (32), as well as increased Na+/K+ pump capacity (1), anaerobic capacity (20) and/or motor unit activation (11,18). Although the acute neuromuscular, physiological and metabolic responses were not directly controlled in the present study, the data reported on the dynamic of HR, BLa and muscular performance parameters during a sprint-distance triathlon before and after a 5-week HIIT plan let us gain some insight into the effectiveness of this training programme. The results showed that a 5-week HIIT-based running plan improved vertical jumping capacity in triathletes, whilst triathletes who continued training at low-moderate intensities with high volumes (CG) did not experience changes in muscular performance variables. Additionally, the regression model performed in this study confirms the relationship between the gains in explosive muscular power and athletic performance improvements during a sprint triathlon. This finding supports the conclusion reported by Nummela et al. (26), who noted the importance of neuromuscular characteristics in determining running economy and, thereby, running performance. Likewise and regarding cycling performance, Faria et al. (15) indicated that peripheral adaptations in working muscles play a more important role for enhanced submaximal cycling capacity than central adaptations. And finally, with regard to the swimming performance improvement (although not statistically significant), the gains reported in explosive muscular power seem to maximise the positive effect of leg kick on the swimming speed - obvious direct generation of propulsive forces from the legs (16).

Hence, the improvements reported in this study highlight the effectiveness of a HIIT-based training programme for improving explosive muscular power and accentuate the importance of neuromuscular performance in endurance performance. Nevertheless, the exact mechanism by which muscular performance improves after a period of HIIT in trained athletes is still unknown. What is clear is that a faster running pace during the HIIT sessions will demand higher levels of neural drive, will lead to higher levels of activation of the anaerobic glycolysis, and will recruit additional fast-twitch motor units for relatively short durations (27), which may be the physiological basis of improvements reported in this study.

Another important finding was the lack of changes in the physiological response during the simulated race at post-test, according to pre-test data. The CG did not experience alterations in athletic performance and, thus, a similar cardiovascular response and BLa might be expected at pre- and post-test. However, the EG improved athletic performance at post-test, which was not accompanied by significant changes in the physiological response during the simulated race nor in exhaustion level reached, which indicates that the triathletes experienced some adaptations that allowed them to race faster with the same physiological impact. A right shift in the lactate threshold, so that higher running speeds are achieved at equivalent BLa levels, is a well-known consequence of endurance training and a determinant of endurance performance (24). Therefore, as well as muscle power improvements, physiological adaptations to the HIIT period might be determinants of athletic performance improvements reported in the current study.

Conclusions

The current study shows that a low-volume HIIT-based running plan combined with the already high training volumes of these triathletes in swimming and cycling, is effective for improving athletic performance during a simulated sprint-distance triathlon competition. This improvement is suggested to be due to improved neuromuscular characteristics that were transferred into improved muscle power and work economy.

Practical applications

From a practical point of view, the current study offers insight into a training method prescription for triathletes by determining the effectiveness of a HIIT-based running programme, which not only causes improvements in muscular performance parameters and allows athletes to enhance their athletic performance in a competition, but also facilitates the reduction of a major risk factor for injury in triathletes such as weekly running distances.

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Table 1. Demographic and anthropometric data of the participants (mean, SD), as well as information about characteristics of their training routines and athletic performance.

Variables	Whole-group (n=13)	Control Group (n=6)	Experimental Group (n=7)	*P-value*
Age (years)	33.8 (5.4)	31.8 (3.2)	35.4 (6.5)	0.181
Body mass (kg)	74.3 (5.8)	74.3 (7.2)	74.3 (5.6)	0.945
Height (m)	1.8 (0.09)	1.8 (0.07)	1.8 (0.06)	0.415
Training volume (hours/week)	15.9 (2.39)	15.2 (2.48)	16.5 (2.32)	0.339
Number of workouts (per week)	9.8 (1.43)	9.8 (1.6)	9.7 (1.48)	0.888
Number of running sessions (per week)	3.5 (0.77)	3.3 (0.81)	3.6 (0.78)	0.654
Running volume (km/week)	31.9 (8.3)	30.0 (7.75)	33.6 (8.9)	0.463
Running volume (hours/week)	4.8 (1.29)	4.3 (1.0)	5.1 (1.26)	0.242
Overall race time (min)	64.9 (6.57)	65.2 (6.69)	64.9 (6.98)	0.912

Table 2. Detailed description of the 5-week HIIT-based running programme, including exercises, intensity prescribed and training volume.

Exercise	Intensity (%VVO_{2max})	Week 1	Week 2	Week 3	Week 4	Week 5
100-m runs with 30-s rest	120-130%	x20	x25	x30	x35	x20
400-m runs with 90-s rest between runs and 3-min between sets	105-110%	2x (4x400m)	2x (5x400m)	2x (5x400m)	2x (5x400m)	2x (3x400m)
Bouts of 120-s runs with 120-s rest	100-105%	x7	x7	x7	x7	--
30-s all-out running sprints with 3-min rest	All-out	--	--	x4	x6	x6
Training volume	session/week	3	3	4	4	3
	km/week	~9.4	~10.7	~11.9	~13.0	~5.7

~ means that training volume, in terms of km per week, might vary according to the metres covered in some exercises

Table 3. Mean heart rate during every stage, and blood lactate accumulation (BLa) and rate of perceived exertion (RPE) after a sprint-distance triathlon race: before (pre-test) and after (post-test) a 5-week intervention period.

	Control group (n=6)		*p-value*	Experimental Group (n=7)		*p-value*
	Pre-test	Post-test		Pre-test	Post-test	
HRmean_Sw (bpm)	169.22 (11.6)	166.37 (13.0)	0.432	170.0 (10.1)	168.92 (11.2)	0.502
HRmean_Cy (bpm)	162.1 (7.65)	164.32 (8.2)	0.491	161.0 (5.43)	163.9 (7.0)	0.501
HRmean_Ru (bpm)	176.83 (10.0)	177.5 (8.21)	0.598	176.43 (12.6)	177 (9.6)	0.547
RPE (6-20)	16.5 (1.8)	17 (1.2)	0.257	15 (1.8)	15.5 (1.1)	0.194
BLa (mmol.kg.min^{-1})	8.87 (2.9)	8.6 (3.1)	0.344	11.5 (3.4)	11.49 (4.3)	0.960

^indicates between groups significant differences at pre-test; HRmean_Sw: mean heart rate during the swimming stage; HRmean_Cy: mean heart rate during the cycling stage; HRmean_Ru: mean heart rate during the running stage

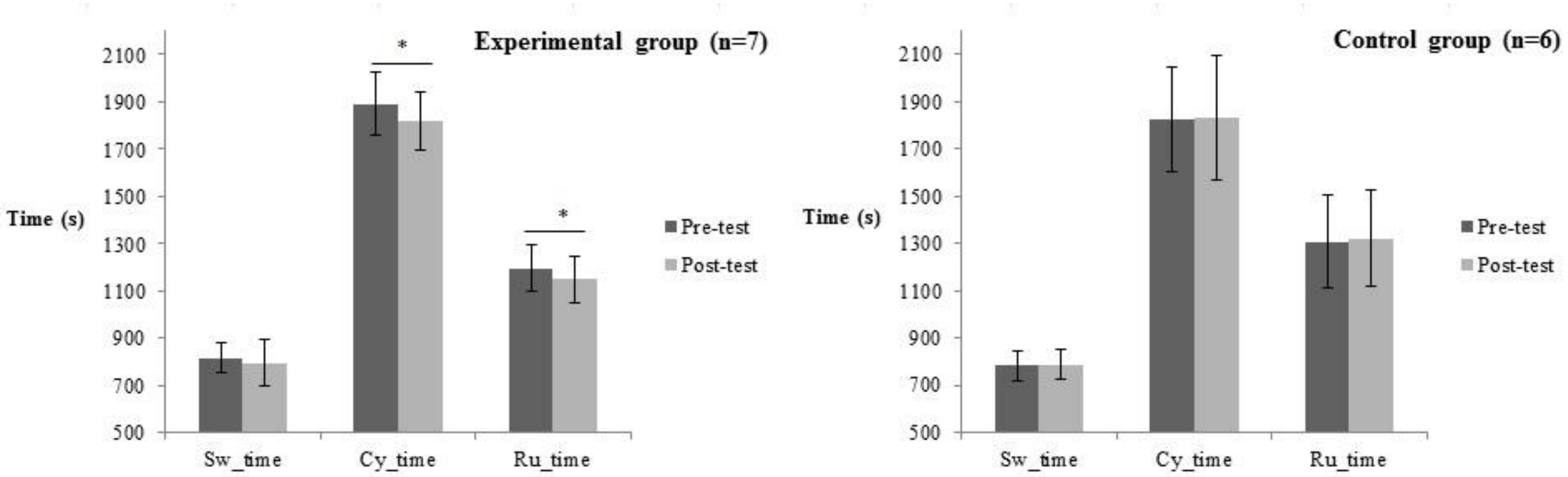

Figure 1. Athletic performance during a sprint-distance triathlon before (pre-test) and after (post-test) a five-week HIIT-based training programme. * $p<0.05$; Sw_time: elapsed time for swimming; Cy_time: elapsed time for cycling; Ru_time: elapsed time for running.

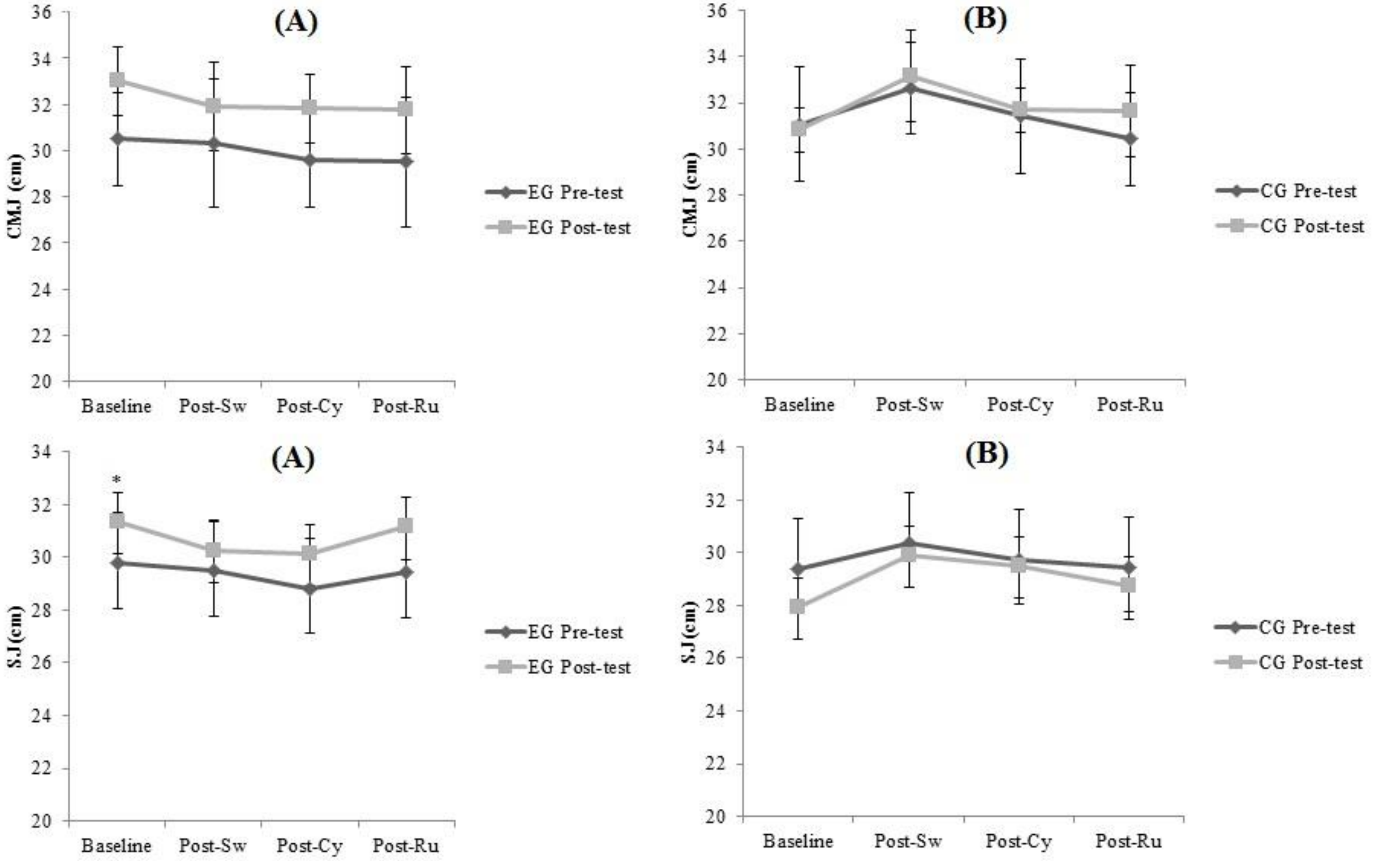

Figure 2. Neuromuscular performance, in terms of vertical jump ability, during a sprint-distance triathlon before (pre-test) and after (post-test) a five-week HIIT-based training programme for experimental (A) and control groups (B). * p<0.05; EG: experimental group; CG: control group; CMJ: countermovement jump; SJ: squat jump; Post-Sw: measurement after the swimming stage; Post-Cy: measurement after the cycling stage; Post-Ru: measurement after the running stage

CONCLUSIONES

- Pese a los altos niveles de fatiga acumulados durante una típica sesión HIIT para atletas de fondo, estos sujetos entrenados son capaces de mantener sus niveles de fuerza y potencia y, por tanto, su capacidad de trabajo.
- El nivel atlético y la edad no resultaron factores influyentes en la respuesta fisiológica y termorreguladora de atletas de fondo a una sesión HIIT (4x3x400 m).
- La cinemática de carrera de atletas de fondo no se vio significativamente alterada tras una sesión HIIT (4x3x400 m). Adicionalmente, ni el nivel del atleta ni el nivel de fatiga alcanzado durante el protocolo resultaron determinantes en las adaptaciones cinemáticas a este entrenamiento, al menos en este grupo de corredores de fondo moderadamente entrenados.
- Los cambios observados en la concentración de metabolitos en sangre (amonio y lactato), además de los cambios en el rendimiento muscular y la respuesta cardiovascular indican que 10×400m and 40×100m son dos protocolos HIIT similares (en términos de impacto metabólico y fisiológico). No obstante, la diferente estructura que presentan permite a los atletas entrenar a mayor ritmo promedio durante el 40×100m.
- Un protocolo con mayor número de carreras cortas (40×100m) ocasionó respuestas neuromusculares diferentes a otro con menor número de carreras más largas (10×400m). El protocolo de 10x400m provocó mejoras en el rendimiento en salto vertical y deterioró el control postural, mientras que el 40x100m no causó cambios significativos en ninguna variable.
- Sesiones HIIT incluyendo carreras de 15-90 s y ejecutadas por encima de la velocidad asociada al VO_{2max}, no deterioraron la cinemática de carrera de atletas de fondo.
- Un plan de carrera basado en bajo volumen y alta intensidad (HIIT), combinado con los altos volúmenes de trabajo que los triatletas acumulan en ciclismo y natación, es efectivo para mejorar el rendimiento durante un triatlón de distancia esprint. Los datos sugieren que esta mejora se debe al incremento de las prestaciones neuromusculares que a su vez se tradujeron en mejoras en la potencia muscular y en la economía de trabajo.

Conclusión general:

A pesar del alto compromiso fisiológico y metabólico reportado durante los protocolos HIIT desarrollados en esta Tesis Doctoral, los atletas de resistencia fueron capaces de mantener sus niveles de potencia y no sufrieron cambios substanciales en su cinemática de carrera. Teniendo en cuenta eso y, el importante rol que juega la intensidad promedio de entrenamiento, el autor sugiere que protocolos HIIT que posibilitan carreras más rápidas (por ejemplo, 40x100 m) parecen ser más eficientes para la mejora del rendimiento de atletas de fondo. Por último, teniendo en cuenta los hallazgos reportados por estudios de intervención basados en HIIT en atletas de fondo, el autor concluye que planes de carrera incluyendo 2-3 sesiones semanales de HIIT, en combinación con sesiones de carrera continua, permiten una mejora del rendimiento atlético fundamentada en la mejora del VO_{2max} y la economía de carrera junto con adaptaciones musculares y metabólicas.

CONCLUSIONS

- Despite high levels of fatigue induced by a typical HIIT for endurance runners (4x3x400 m), trained subjects can maintain their strength and power levels and their work capacity.
- The differences in athletic performance or age did not substantially alter the acute physiological and thermoregulatory responses to a typical HIIT workout (4x3x400 m) for endurance runners - as long as HIIT was performed at similar relative intensity.
- A common HIIT session (4x3x400 m) for endurance runners did not consistently perturb their running kinematics. Additionally, neither athletic performance nor exhaustion level reached seems to be determinant in the kinematic response during a HIIT, at least for this group of moderately-trained endurance runners.
- The changes observed in blood metabolites (BLa and BAmm), as well as the power output changes, and the acute cardiovascular response indicate that 10×400m and 40×100m are two very similar HIIT protocols in terms of metabolic and physiological impact. Nevertheless, training differences allow runners to train at a higher pace during the 40×100m.
- A protocol with a higher number of shorter runs (40×100m) induced different changes in those neuromuscular parameters than those with fewer and longer runs (10×400m).Whereas the 40×100m protocol did not cause any significant changes in vertical jump ability, postural control, or SSC utilisation, the 10×400m protocol impaired postural control (in terms of CoP movement) and caused improvements in vertical jumping tests.
- HIIT sessions including runs for 15-90 seconds and performed at intensity above velocity associated to maximal oxygen uptake, did not consistently perturb the running kinematics of trained endurance runners. Since previous studies had suggested that 40×100m might be a more efficient HIIT for improving the performance of endurance runners, this study reinforces that statement with no kinematic alterations during any of those running exercises.
- A low-volume HIIT-based running plan combined with the already high training volumes of these triathletes in swimming and cycling, is effective for improving athletic performance during a simulated sprint-distance triathlon competition.

This improvement is suggested to be due to improved neuromuscular characteristics that were transferred into improved muscle power and work economy.

Overall conclusion:

Despite high-level of physiological and metabolic strain showed during the HIIT workouts performed in this project, endurance runners maintained their power levels and did not substantially perturb running kinematics. Based on that finding and considering the importance of mean training intensity, the author suggest that intermittent protocols including faster runs (i.e., 40x100 m) appears to be a more efficient HIIT for improving the performance of endurance runners. Finally, taken into consideration the intervention studies focused on HIIT and endurance runners, HIIT-based running plans (two to three HIIT sessions per week, combining HIIT and continuous runs) showed athletic performance improvements in endurance runners by improving VO_{2max} and running economy along with muscular and metabolic adaptations.

PROSPECTIVAS FUTURAS DE ESTUDIO

El conocimiento acerca de, tanto cambios agudos inducidos por protocolos HIIT como adaptaciones a largo plazo provocadas por programas de intervención basados en HIIT en corredores de fondo, juega un papel muy importante en la prescripción del entrenamiento deportivo. Un mayor conocimiento permitirá a los entrenadores ser más precisos con las cargas de entrenamiento. No obstante, teniendo en cuenta que muchas variables pueden ser manipuladas en la prescripción de HIIT y, que la manipulación de cada variable tiene un impacto directo en la respuesta neuromuscular, metabólica y cardiopulmonar, diferentes protocolos HIIT de carrera deben ser examinados con el objetivo de enriquecer la información disponible sobre ese impacto agudo y, consecuentemente, facilitar la periodización y programación del entrenamiento.

Adicionalmente, la presente Memoria de Tesis Doctoral se centra en adaptaciones agudas y a largo plazo a sesiones e intervenciones HIIT, mientras no se consideró la respuesta a corto- medio plazo. La respuesta fisiológica, metabólica y neuromuscular a seis, doce, veinticuatro, cuarenta y ocho, setenta y dos horas post-ejercicio, aporta una información enormemente relevante para la correcta prescripción de entrenamiento. Por tanto, más estudios monitorizando la respuesta a diferentes protocolos HIIT durante, al menos, tres días tras el entrenamiento, son claramente necesarios.

Finalmente, otras investigaciones que se centren en el análisis de ocurrencia y prevalencia de lesiones durante programas de entrenamiento basados en HIIT con atletas de resistencia pueden resultar relevantes. El efecto de estos protocolos HIIT en marcadores relacionados con el riesgo de lesión, como puedan ser las fuerzas de impacto en extremidades inferiores o el compromiso y solicitación neuromuscular, aún son ampliamente desconocidas; de modo que, se requiere de mayor información sobre el riesgo de lesión y la ocurrencia de lesiones tanto a corto, medio y/o largo plazo en atletas de resistencia implicados en protocolos HIIT.

PROSPECTS FOR FUTURE RESEARCH

Knowledge about either the acute changes induced by HIIT protocols or the long-term adaptations induced by HIIT-based interventions in endurance runners plays a key role in the training prescription process. A further knowledge will let coaches be more accurate with workloads. Nevertheless, since many variables can be manipulated to prescribe HIIT and, the manipulation of each variable has a direct impact on metabolic, cardiopulmonary and/or neuromuscular responses, more HIIT protocols must be examined.

Additionally, the current PhD Thesis focuses on acute responses and long-term adaptations after a HIIT intervention with short-term adaptations being not considered. The physiological, metabolic and neuromuscular response at six, twelve, twenty-four, forty-eight, seventy-two hours post-exercise provides essential information to prescribe a well-balanced training programme. Therefore, more studies monitoring the response to different HIIT protocols within, at least, three days post-exercise, are clearly needed.

Finally, more research evaluating injury occurrence during HIIT-based running plans is needed. The effects of more strenuous runs on markers related to risk of injury, such as impact forces on the lower limbs or neuromuscular engagement, are still unknown so that, further knowledge is required about either short- and long-term risk of injury and injury occurrence in endurance runners.

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Aportaciones a Congresos

(Únicamente se citan las relacionadas con la presente tesis)

1. **García-Pinillos F,** Latorre-Román PA, Párraga-Montilla J (2015). Respuesta neuromuscular de atletas de resistencia a un entrenamiento interválico extensivo. *I Congreso Iberoamericano Desporto, Educacao, Actividade Fisica e Saude,* 22-25 Octubre de 2015 (Lisboa, Portugal)
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