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Estudio de la potencia como alternativa a los protocolos de laboratorio para el análisis del rendimiento en el ciclismo de carretera.

Director/es

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ESTUDIO DE LA POTENCIA COMO ALTERNATIVA A LOS PROTOCOLOS DE LABORATORIO PARA EL ANÁLISIS DEL RENDIMIENTO EN EL CICLISMO DE CARRETERA

ZARAGOZA, JUNIO 2021

Universidad Zaragoza

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AUTOR: SEBASTIAN JAN SITKO

"Una cosa es sentir que vas por el camino correcto y otra muy distinta es pensar que el tuyo es el único camino"

Paulo Coelho

Estudio de potencia como alternativa a los protocolos de laboratorio para el análisis de rendimiento en el ciclismo de carretera

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Que la Tesis Doctoral titulada "Estudio de potencia como alternativa a los protocolos de laboratorio para el análisis del rendimiento en el ciclismo de carretera" que presenta D. **SEBASTIAN SITKO** al superior juicio del Tribunal que designe la Universidad de Zaragoza, ha sido realizada bajo mi dirección durante los años 2019-2021, siendo expresión de la capacidad técnica e interpretativa de su autor en condiciones tan aventajadas que le hacen merecedor del Título de Doctor, siempre y cuando así lo considere el citado Tribunal.

Fdo. Isaac López Laval

En Zaragoza, a 16 de junio de 2021

Universitat de Lleida

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Fdo. Francisco Corbi Soler

En Lleida, a 16 de junio de 2021

Proyectos de investigación:

Esta tesis está basada en un proyecto autofinanciado.

Todos los materiales y recursos que aparecen en este trabajo han sido obtenidos sin la intervención de terceras partes.

Índice

Listado de abreviaturas

ATP:	Adenosina trifosfato
CO_2:	Dióxido de carbono
FC:	Frecuencia cardiaca
MLSS:	Máximo estado estable de lactato
OBLA:	Onset of Blood Lactate Accumulation
PCR:	Punto de compensación respiratoria
$PETCO_2$:	Presión parcial del dióxido de carbono en la espiración
$PETO_2$:	Presión parcial del oxígeno en la espiración
RER:	Cociente respiratorio
UPF:	Umbral de potencia funcional
VE/VO_2:	Equivalente ventilatorio del oxígeno
VE/VCO_2:	Equivalente ventilatorio del dióxido de carbono
VO_2:	Consumo de oxígeno
VCO_2:	Producción de dióxido de carbono
VO_{2max}:	Consumo máximo de oxígeno
VT1:	Primer umbral ventilatorio
VT2:	Segundo umbral ventilatorio
W:	Vatio

Resumen

Los estudios de laboratorio han sido considerados tradicionalmente como el método más idóneo para el análisis del rendimiento en ciclistas. Sin embargo, este tipo de procedimientos está asociado a diversas limitaciones como el elevado coste económico y temporal, la necesidad de recursos humanos cualificados y el acceso a un material técnico específico. Además, este tipo de pruebas no permiten determinar con precisión parámetros máximos y submáximos de rendimiento en una misma sesión. En los últimos años, el uso de potenciómetros se ha extendido ampliamente en los campos profesional y aficionado. Esta herramienta de valoración no está sujeta a condicionantes propios del estudio de otros marcadores de control, tales como la FC, la percepción subjetiva del esfuerzo o la velocidad, permitiendo un análisis más preciso de la demanda fisiológica a la que el ciclista está sujeto en todo tipo de condiciones. La posibilidad de estimar parámetros fisiológicos clásicos a través de datos de potencia supone una importante ventana de oportunidad para el análisis del rendimiento por parte de ciclistas, entrenadores y científicos. Esta tesis doctoral analiza retrospectivamente la literatura científica que guarda relación con el entrenamiento a partir de la potencia en el ciclismo de carretera para posteriormente tratar de determinar una fórmula predictiva del consumo máximo de oxígeno a partir de los datos de potencia desarrollados por el ciclista. En los apartados siguientes, se estudia la estrecha relación existente entre el umbral de potencia funcional, el punto de compensación respiratoria, la lactacidemia fija de 4 mmol/L y los umbrales de lactato determinados a través de los métodos Dmax y Dmax modificado. Finalmente, se presenta un análisis exhaustivo de la potencia generada por los ciclistas durante la realización de un evento cicloturista masivo, tratando de proyectar el rendimiento a partir de los datos individuales de potencia. El presente trabajo demuestra la capacidad predictiva y evaluadora del rendimiento que tiene la potencia en el ciclismo de carretera.

Abstract

Laboratory studies have traditionally been considered the most suitable method for the analysis of cycling performance. However, these types of procedures are associated with several limitations such as the economic cost, the time-consuming nature of the assessments, the need for specific materials and educated staff, or the impossibility of accurately studying maximum and sub-maximum performance parameters in the same session. In recent years, the use of power meters has spread widely in the professional and amateur fields. This type of tool is not subject to the limitations inherent to other markers such as heart rate, subjective perception of effort or speed and allows a precise analysis of the physiological demand to which the cyclist is subjected in all types of situations. The possibility of estimating classical physiological parameters through power data represents an important window of opportunity for performance analysis by cyclists, coaches, and scientists. In this doctoral thesis, in the first place, a retrospective analysis of the scientific literature related to power-based training in road cycling was performed. Then, a new formula for the determination of the maximum oxygen consumption of cyclists based on their power data was proposed. The following sections assessed the close relationship between the functional threshold power, the respiratory compensation point, fixed lacticaemias of 4 mmol / L, and lactate thresholds determined through Dmax and modified Dmax methods. Finally, an analysis of a famous cyclosportive event was presented together with a new power-based method for the prediction of performance. This work shows the predictive and evaluative capacity of power output in the sport of road cycling.

Prólogo

La fisiología deportiva es una disciplina científica que intenta explicar el impacto orgánico y funcional del ejercicio sobre el cuerpo humano. Sus orígenes se remontan a la antigua Grecia, donde Hipócrates, en sus 87 tratados de medicina, incluía recomendaciones sobre la salud y la higiene como primeros acercamientos al estudio del impacto del ejercicio sobre el organismo humano. Cinco siglos después, Galeno profundizó en estos conocimientos y realizó recomendaciones explícitas sobre como debía ser la práctica de ejercicio físico para el mantenimiento de la salud y prescribió distintos entrenamientos con el objetivo de aliviar determinadas dolencias (Tipton, 2015). A pesar de estas referencias, debemos remontarnos a finales del siglo XIX para encontrar el nacimiento de la fisiología deportiva moderna. En esta época, autores como Flint o Hitchcock realizaron las primeras antropometrías, recurriendo al uso de analizadores de gases y cardiógrafos para medir la respuesta orgánica al ejercicio. En esta época y hasta la segunda década del siglo XX, el laboratorio de fisiología de Harvard fue el centro puntero de la disciplina a nivel mundial (Johnson, 2015). Paralelamente, científicos de otras nacionalidades seguían progresando en esta materia. En la década de los años 30, Lindhard y Krogh, dos profesores de la universidad de Copenhague, investigaron el intercambio de gases en los pulmones. Ambos fueron pioneros en los estudios de la contribución relativa a la oxidación de grasas e hidratos de carbono durante el ejercicio, midiendo la redistribución del flujo sanguíneo durante la practica de actividad física a diferentes intensidades, y cuantificando además la dinámica cardiorrespiratoria (McArdle, Katch, & Katch, 2015). Un estudiante de la misma universidad (Christensen), expuso sus estudios sobre gasto cardíaco, temperatura corporal y concentración de glucosa en sangre durante el ejercicio intenso en cicloergómetro, en los que comparó ejercicios de brazos y piernas y cuantificó los efectos del entrenamiento (McArdle et al., 2015). En 1936, Christensen publicó junto con Krogh y Lindhard una importante reseña que describió la dinámica fisiológica durante el ejercicio de máxima intensidad. Junto a Hansen, utilizaron la captación de oxígeno y el cociente respiratorio para describir cómo la dieta, el entrenamiento y la intensidad y duración del ejercicio afectaban a la utilización de hidratos de carbono y grasas (McArdle et al., 2015).

El centro fisiológico de referencia a mediados de siglo XX fue el Karolinska Institute de Suecia. En este centro, Astrand desarrolló una nueva línea de investigación sobre las respuestas fisiológicas al ejercicio intermitente, estudios que le otorgaron fama a nivel mundial. Ya en la década de los 60, Bergström y Hultman, del mismo Karolinska Institute, desarrollaron las primeras biopsias con aguja durante el ejercicio. Con esta técnica se pudo estudiar por primera vez el músculo en diferentes situaciones de entrenamiento y dieta (Åstrand, 2007). En los últimos años Saltin ha sido el autor de referencia. Este fisiólogo proporcionó importantes aportaciones en diversos campos tales como la descripción del deterioro de la capacidad y condición física de las personas sometidas a inactividad, así como el intercambio de oxígeno a nivel central y periférico. Estas líneas de trabajo permitieron conocer los mecanismos intrínsecos de distribución del principal metabolito de oxidación (Joyner, 2017). Sus estudios a través de biopsias musculares, junto con López-Calbet, han permitido explicar el flujo sanguíneo y de sustratos en el músculo como factor determinante del envejecimiento humano. Sus experimentos han contribuido a desmentir el reduccionismo en torno al balance energético positivo como único y principal causante del sobrepeso (Joyner, 2017). A día de hoy la fisiología del ejercicio es una ciencia en constante expansión. El número de revistas y artículos sobre la materia ha aumentado exponencialmente en los últimos años, hecho que se ve reflejado en el desarrollo de nuevas herramientas y sistemas de medición, que a su vez permiten un conocimiento mucho más profundo de las respuestas del organismo humano al ejercicio (McArdle et al., 2015).

1. Introducción y marco teórico

1.1 Bases de la fisiología del ejercicio

1.1.1 Respuesta fisiológica al ejercicio

El organismo humano responde al estímulo del ejercicio con una activación metabólica, cardiovascular y ventilatoria que le permite obtener energía a partir de los sustratos principales y oxígeno para la combustión de dichos sustratos en las células. El grado de activación del organismo como respuesta al ejercicio dependerá de diversas condiciones medioambientales, así como de la duración, intensidad y frecuencia del ejercicio (Burton, Stokes, & Hall, 2004).

1.1.1.1 Sustratos energéticos

El ATP es considerado el mediador químico de referencia para la realización de trabajo mecánico en seres vivos. Al comienzo del ejercicio, las reservas de este sustrato que se obtienen mediante el sistema del fosfágeno sólo permiten la realización de trabajo por una duración de tiempo extremadamente limitada (1-2 segundos), por lo que son necesarias alternativas para la obtención del ATP de manera rápida. De esta manera, el músculo esquelético almacena fosfocreatina, que es utilizada durante los primeros 10 primeros segundos del ejercicio antes de pasar a la utilización de otros sustratos energéticos. Para el ejercicio de duración superior, la obtención de energía proviene de la glucólisis, proceso en el que la glucosa y el glucógeno se convierten en piruvato y entran en el ciclo de Krebs para sintetizar nuevamente ATP. Este proceso puede darse en presencia de oxígeno, obteniéndose grandes cantidades de energía en periodos prolongados. Por otro lado, la obtención anaeróbica de ATP resulta en cantidades de energía más modestas, que se utilizan tras el agotamiento de la fosfocreatina para prolongar el tiempo de ejercicio máximo hasta el minuto o minuto y medio (McArdle et al., 2015). Como consecuencia de este proceso anaeróbico se produce y acumula el lactato. Finalmente, los ácidos grasos pueden oxidarse y entrar en el ciclo de Krebs para la producción de energía aeróbica. Este tipo de energía, si bien proviene de fuentes casi inagotables en el organismo, tiene la limitación de la baja tasa de resíntesis de ATP de las grasas y su participación en el ejercicio de alta intensidad es muy baja (Åstrand, Rodahl, Dahl, & Strømme, 2003; Powers & Howley, 1995). En la Tabla I se representa de manera esquemática las principales vías metabólicas utilizadas durante el ejercicio, los sustratos característicos de cada una de ellas, su plazo y duración de la acción.

Tabla I: Sistemas energéticos y sus principales características, según Pancorbo (2008)

Fuentes	Vías de formación	Tiempo inicio	Plazo acción	Tiempo de liberación
Anaeróbica aláctica	Fosfágenos, fosfocreatina	0’’	30’’	10’’
Anaeróbica láctica	Glucólisis anaeróbica	15-20’’	30’’- 5/6’	30’’-1’30’’
Aeróbica	Oxidación carbohidratos y grasas	90-180’’	Hasta varias horas	2-5’

1.1.1.2 Respuesta ventilatoria al ejercicio

Durante el ejercicio de intensidad submáxima se produce un aumento de la ventilación y del consumo de oxígeno proporcional al trabajo requerido. Este incremento es consecuencia del aumento de la frecuencia respiratoria y del volumen de aire que circula entre inspiración y espiración, siendo éstas a su vez respuestas propias del cambio de intensidad (Kenney, Wilmore, & Costill, 2015). En intensidades máximas, se produce un aumento del consumo de oxígeno y de la ventilación. Al contrario de lo que ocurre en la realización de actividades de intensidad submáxima, el incremento que se genera en este tipo de esfuerzos no resulta proporcional al trabajo requerido. Este fenómeno ocurre debido al incremento de la glucólisis y la acumulación de lactato, que producen un aumento de la presión parcial de CO_2 en las arterias (McArdle et al., 2015). Como respuesta a esta situación metabólica se produce un aumento de la ventilación, provocando un descenso de la presión parcial de CO_2 para compensar la acidificación producida por la acumulación de ácido láctico (McArdle et al., 2015) .

1.1.1.3 Respuesta circulatoria al ejercicio

Durante el ejercicio, debido a la vasodilatación generada, el volumen sanguíneo que llega al músculo se incrementa, produciéndose además un incremento de la demanda sanguínea en la piel, con el fin de conseguir una disipación del calor más eficiente. Esta modificación en la circulación sanguínea se produce gracias al aumento en el gasto cardiaco provocado por el incremento del volumen sistólico y de la FC (Burton et al., 2004). Una de las adaptaciones al ejercicio que se producen en deportistas es la hipertrofia ventricular o hipertrofia cardiaca, una modificación estructural que el entrenamiento genera y que permitirá incrementar el gasto cardiaco como consecuencia del incremento del volumen sistólico. A pesar de este incremento que se produce como consecuencia de la adaptación al entrenamiento, la FC permanece estable e incluso en la mayoría de ocasiones disminuye (Degens et al., 2019). Otra de las adaptaciones producidas es el ligero aumento de la tensión arterial como consecuencia tanto del incremento del gasto cardiaco como del retorno venoso. La función cardiovascular es el factor limitante para oxigenar los tejidos durante el ejercicio, ya que éstos no pueden procesar más oxígeno que aquel que puede ser transportado por la sangre (Hackney, 2019).

1.1.1.4 Respuesta periférica al ejercicio

Las fibras musculares se pueden clasificar en tipo I, IIa y IIb (Karp, 2004). La predominancia de cada tipo de fibra varía según el músculo, su rol y factores hereditarios. La predominancia de uno u otro tipo de fibra en el organismo marcará la predisposición genética para determinados deportes (Powers & Howley, 1995). Al margen de las adaptaciones centrales mencionadas anteriormente, el ejercicio físico conlleva una serie de cambios a nivel periférico que son muy dependientes no solo del tipo de ejercicio sino también de su duración e intensidad. Estas adaptaciones engloban todos los cambios que ocurren en el músculo y en los tejidos circundantes como respuesta al entrenamiento (Åstrand et al., 2003). Entre los más destacados podemos encontrar el aumento en la densidad y el número de capilares, los cambios en la densidad y en el número de mitocondrias o los propios de la actividad enzimática (McArdle et al., 2015). De esta manera, el tipo de entrenamiento seguido por el deportista tendrá un impacto la eficiencia para la oxidación de los diferentes sustratos: el entrenamiento interválico de alta intensidad incide sobre las fibras tipo IIb y la vía del fosfágeno, fosfocreatina y glucolítica anaeróbica, mientras que el entrenamiento aeróbico incide sobre las fibras tipo I y la vía de la oxidación de hidratos de carbono y ácidos grasos, junto con toda la actividad enzimática que participa en dicha conversión (McArdle et al., 2015). A pesar de que históricamente se han considerado a las adaptaciones centrales como prerrequisitos fundamentales para el rendimiento, los estudios publicados en los últimos años apuntan hacia la las adaptaciones periféricas, como elemento diferenciador entre deportistas con un nivel basal similar (Jeukendrup & Gleeson, 2020). En la Tabla II se presentan las características predominantes de cada uno de los tipos de fibra muscular.

Tabla II. Tipología de fibras musculares y sus características según Karp (2004)

Características	**Fibras tipo I**	**Fibras tipo IIa**	**Fibras tipo IIb**
Tiempo de contracción	Lento	Rápido	Muy rápido
Tamaño del axón motor	Pequeño	Grande	Muy grande
Resistencia a la fatiga	Alta	Intermedia	Baja
Actividad preferente	Aeróbica	Anaeróbica larga	Anaeróbica corta
Producción de fuerza	Baja	Alta	Muy alta
Densidad mitocondrial	Alta	Alta	Baja
Densidad capilar	Alta	Intermedia	Baja
Capacidad oxidativa	Alta	Alta	Baja
Capacidad glucolítica	Baja	Alta	Alta
Principal sustrato	Triglicéridos	Fosfocreatina, glucógeno	Fosfocreatina, glucógeno

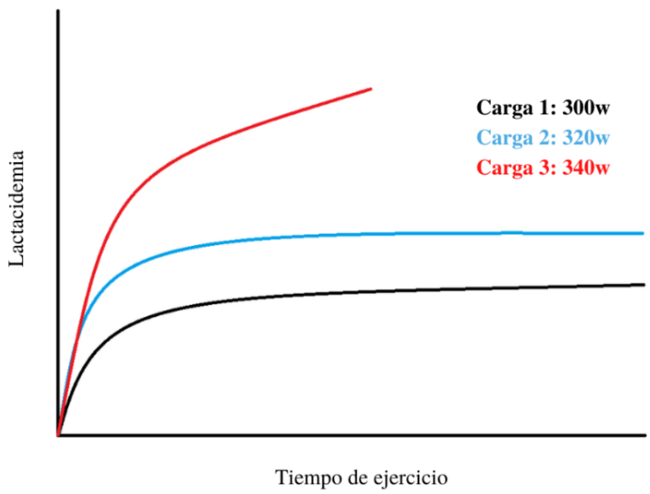
1.1.2 Principales hitos fisiológicos del deporte de resistencia

El organismo humano, cuando es expuesto a los requerimientos propios del ejercicio físico con demandas incrementales, sufre una ruptura en su estado de homeostasis. Estos hitos fisiológicos son medibles en laboratorio y se clasifican, en función de su naturaleza, en ventilatorios y lácticos. Históricamente, se han utilizado estos umbrales para determinar la intensidad del entrenamiento y cuantificar la carga. No obstante, el uso indistinto de estos hitos conlleva limitaciones ya que, en general, no se localizan a intensidades del ejercicio equivalentes.

1.1.2.1 Hitos basados en el estudio del lactato

La medición del lactato sanguíneo se utiliza de manera muy frecuente en la medicina deportiva, debido a que ésta es un excelente marcador del rendimiento en las disciplinas de resistencia (Faria, Parker, & Faria, 2005). El análisis de la producción de lactato se realiza normalmente en condiciones de laboratorio, en las que el deportista es sometido a cargas incrementales de trabajo, mientras la concentración sanguínea de lactato se evalúa a determinados intervalos de tiempo. En el ejercicio de alta intensidad, el lactato se forma en el músculo junto a los iones de hidrógeno, hecho que incitará una mayor eliminación del lactato del plasma sanguíneo (McArdle et al., 2015). Sin embargo, a partir de una determinada carga de trabajo, el proceso de eliminación se satura y el lactato comienza a acumularse en la sangre, momento que coincide con la transición aeróbica-anaeróbica (Wasserman et al., 1994). La intensidad asociada a esta situación se considera como hito de relevancia para la evaluación del rendimiento de un deportista de resistencia (Płoszczyca et al., 2020). Clásicamente, el valor de referencia a determinar dentro de los parámetros lácticos ha sido el MLSS. Este parámetro se define como la máxima concentración de lactato sanguíneo que puede ser mantenida a través del tiempo sin acumulación continua en sangre (Borszcz et al., 2018). La carga de trabajo asociada a este hito resulta crucial para el deportista de resistencia debido a que determina la máxima intensidad a la que puede permanecer durante periodos de tiempo prolongados. Para determinarlo, es necesaria una valoración a través de diferentes cargas de trabajo a lo largo de días distintos para poder establecer de una manera eficaz la mayor carga soportable en el tiempo (Faude, Kindermann, & Meyer, 2009).

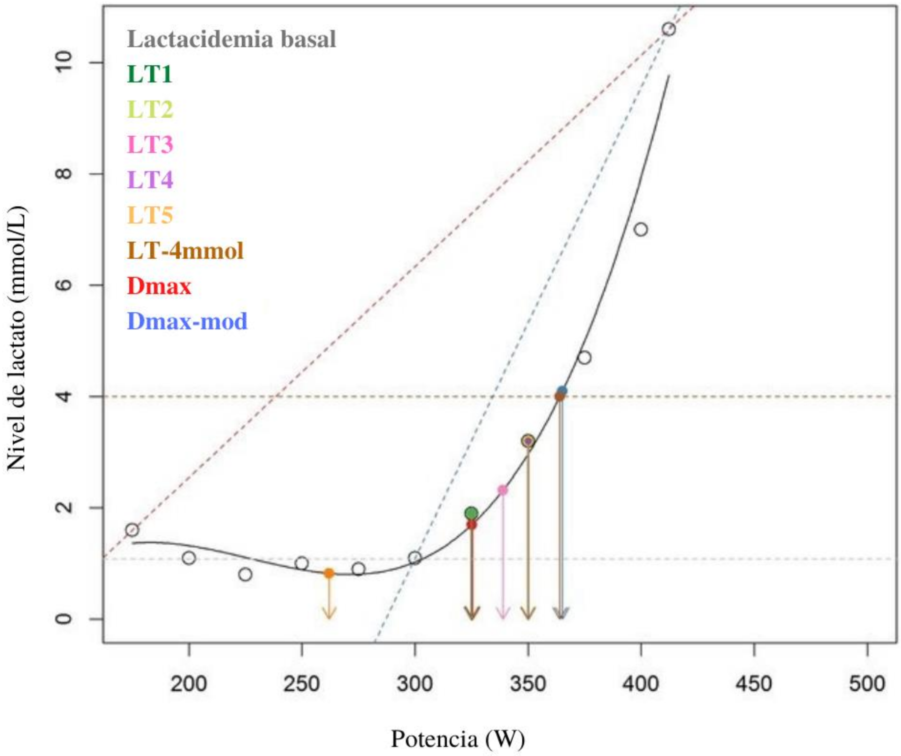
Figura 1. Determinación del máximo estado estable de lactato. El MLSS en este caso estaría representado con la línea azul.



A pesar de su gran relevancia, la poca practicidad asociada al testeo del MLSS ha tenido como consecuencia la aparición en la literatura científica de hasta 25 hitos lácticos distintos que pueden determinarse durante una prueba incremental de laboratorio. Estos hitos son utilizados de un modo poco concreto en los estudios científicos actuales, a pesar de que han sido estudiados en muestras de deportistas de diferentes especialidades deportivas. En la mayoría de ocasiones, estos hitos fisiológicos se determinan a cargas de trabajo variables, por lo que su capacidad predictiva y repetibilidad debería ser considerada con cautela (Heuberger et al., 2018).

Los distintos umbrales lácticos propuestos en estudios previos podrían ser clasificados en diversos grupos según su metodología de determinación. Entre los hitos fácilmente identificables de manera visual podemos encontrar las lactacidemias fijas de 2 y 4 mmol/L y los incrementos fijos de lactato sobre el estado basal. Por otro lado, existen métodos de determinación más complejos que requieren de un ajuste polinómico de tercer grado en la curva de producción de lactato. Este parámetro puede obtenerse al dividir el lactato entre la potencia o el consumo de oxígeno para encontrar el mínimo equivalente entre ambas variables o mediante la búsqueda de la mayor distancia perpendicular entre la línea derivada del ajuste polinómico y las diversas tomas de lactato realizadas durante un test incremental (Cerezuela-Espejo et al., 2018; Heuberger et al., 2018; Pallarés et al., 2016). Entre estos últimos métodos, destacan por repetitividad y gran correlación con el rendimiento en deportes de resistencia el Dmax y el Dmax modificado, así como por su capacidad predictiva el MLSS (Chalmers, Esterman, Eston, & Norton, 2015; Heuberger et al., 2018; Pallarés et al., 2016). La Figura 2 muestra el comportamiento esperado de la curva de lactato durante una prueba incremental, así como la localización de los hitos lácticos más importantes reportados en la literatura.

Figura 2. Representación gráfica de los principales hitos lácticos, adaptada de Heuberger (2018).



Círculos abiertos: valores de lactato tomados a diversas intensidades; Línea continua negra: polinomial de tercer orden; Línea discontinua gris: valor basal; LT1: Primer incremento de lactato; LT2: primer incremento de 1 mmol/L sobre el estado basal; LT3: Mínimo equivalente de lactato (lactato dividido por potencia + 1.5 mmol/L); LT4: primer incremento de 1 mmol/L al respecto del valor anterior; LT5: Mínimo equivalente de lactato (lactato dividido por consumo de oxígeno); LT-4mmol: lactacidemia fija de 4 mmol/L; Dmax: valor con la máxima distancia perpendicular al polinomial desde la línea discontinua; Dmax-mod: valor con la máxima distancia perpendicular al polinomial desde la línea discontinua.

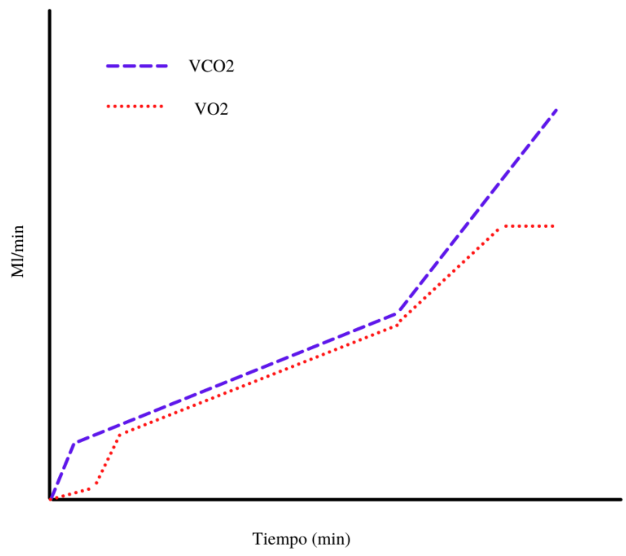
1.1.2.2 Hitos basados en el estudio de parámetros ventilatorios

Durante el ejercicio de intensidad moderada, el consumo de oxígeno (VO_2) y la producción de dióxido de carbono (VCO_2) aumentan de manera proporcional (Beaver, Wasserman, & Whipp, 2016). Si la intensidad del ejercicio sigue subiendo, se produce una mayor participación del sistema glucolítico por la mayor utilización de fibras tipo II. Los iones de hidrógeno producidos como consecuencia de la utilización del lactato son tamponados por el bicarbonato, produciéndose un aumento del VCO_2 y de la ventilación (Pallarés et al., 2016). Se conoce como primer umbral ventilatorio (VT) a la intensidad del ejercicio correspondiente con la pérdida de la linealidad de la ventilación junto con el inicio del aumento del equivalente ventilatorio para el oxígeno (VE/VO_2) y de la presión parcial de oxígeno en la espiración ($PETO_2$), mientras se mantienen estables los niveles del equivalente ventilatorio del dióxido de carbono (VE/VCO_2) y la presión de bióxido de carbono al final de la espiración ($PETCO_2$) (Poole et al., 2020).

Al aumentar la intensidad por encima del primer umbral ventilatorio, se deteriora la capacidad de amortiguación del lactato, produciéndose aumento del VE/VCO_2 y de la presión de CO_2 al final de la espiración ($PETCO_2$). Además, se observa una disminución de la presión arterial de CO_2, del pH y un aumento del cociente respiratorio (RER). Este hito fisiológico se conoce como umbral ventilatorio 2 (VT2) o punto de compensación respiratoria (PCR) (Poole et al., 2020). La intensidad del ejercicio asociada a este umbral suele representar el máximo estado estable metabólico y las intensidades superiores suponen una ruptura de la homeostasis metabólica que tiene como consecuencia un tiempo limitado hasta el agotamiento (Wasserman et al., 1994).

A intensidades superiores, podemos encontrar el consumo máximo de oxígeno o VO_{2max}. Este punto fisiológico se define como la cantidad máxima de oxígeno que un organismo puede absorber, transportar y consumir en un tiempo determinado (Faria et al., 2005). Se trata del marcador cardiorrespiratorio por excelencia, es un prerrequisito para el alto rendimiento en el deporte de resistencia y es la manera más eficaz de medir la capacidad aeróbica de un individuo (Poole & Jones, 2017). Para una mayor concreción y con la intención de poder comprar individuos entre si, se suele expresar relativizado a la masa corporal (ml/kg/min). Históricamente, los deportistas de resistencia de élite como los ciclistas de carretera presentan valores superiores a los 70ml/kg/min (De Pauw et al., 2013). El tiempo límite en el que se puede mantener dicha intensidad varía entre los 3 y los 6 minutos según estudios previos (Caputo, Mello, & Denadai, 2003). Uno de los métodos más populares para la obtención de VO_{2max} en un test incremental consiste en la visualización de la meseta del VO_2, técnica que se basa en el principio de que, a partir de una determinada intensidad no se puede seguir produciendo un aumento del consumo de oxígeno, ya que este sufre un estancamiento (Lucía et al., 2006). No obstante, este fenómeno no se observa en todas las pruebas de esfuerzo y en ocasiones el fisiólogo debe utilizar los llamados criterios secundarios para la determinación del VO_2 pico (Poole & Jones, 2012). Por ello, entre otros parámetros, se suele recurrir asiduamente a la FC máxima teórica, al cociente respiratorio, a la percepción subjetiva del esfuerzo o al control de la lactacidemia (Poole & Jones, 2017). En la figura 2 se representa el comportamiento del consumo de oxígeno y la producción del dióxido de carbono durante una prueba de esfuerzo incremental.

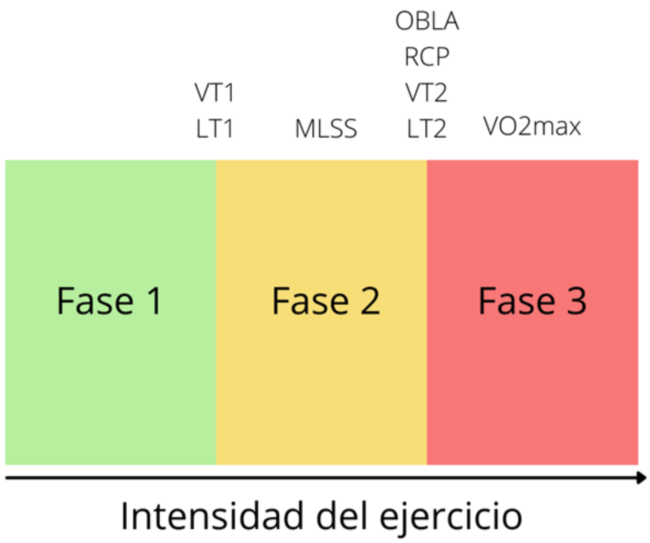
Figura 3. Evolución del VO_2 y VCO_2 durante una prueba de esfuerzo incremental



1.1.2.3. Modelo trifásico del ejercicio

La evidencia científica reciente sugiere que el entrenamiento basado en umbrales submáximos determinados de manera individual produce, en el deporte de resistencia, adaptaciones superiores a aquellas que se observan con un entrenamiento basado en porcentajes estandarizados obtenidos a partir de valores máximos (FC, VO_{2max}, etc) (Weatherwax et al., 2019). Ya en 1980, Skinner y McLellan presentaron su propuesta de representación de la transición aeróbica-anaeróbica durante el ejercicio progresivo e incremental. En este modelo, las intensidades del ejercicio se dividen en tres categorías en función de las vías metabólicas utilizadas. Varios de los hitos fisiológicos mencionados en los capítulos anteriores servían a modo de umbrales delimitantes entre las distintas fases propuestas en el modelo (Skinner & McLellan, 1980). La finalidad última de la propuesta era facilitar el entrenamiento y la cuantificación de la carga gracias a una determinación individual de los umbrales. La primera fase abarcaba desde el reposo hasta la intensidad correspondiente al primer umbral ventilatorio o láctico. Se trata de una fase estable, con predominancia del metabolismo aeróbico. En la segunda fase se produce un cambio en la pendiente de la curva, tanto láctica como ventilatoria, y el metabolismo aeróbico comparte protagonismo con la cada vez más presente glucólisis anaeróbica. La segunda y tercera fase están delimitadas por el segundo umbral ventilatorio o láctico y se caracterizan por la ruptura total de la homeostasis y un tiempo hasta el agotamiento limitado (Skinner & McLellan, 1980). La principal importancia de este modelo radica en el énfasis que se pone sobre la relevancia de la variabilidad interindividual en los hitos fisiológicos submáximos, que a su vez delimitan rupturas de la homeostasis que deben tenerse en cuenta a la hora de planificar el proceso de entrenamiento (Weatherwax et al., 2019). En la figura 4 se presenta el modelo trifásico de Skinner y McLellan con la localización de los principales hitos fisiológicos descritos en las secciones previas.

Figura 4: Modelo trifásico propuesto por Skinner y McLellan (1980) con la localización de los distintos hitos fisiológicos en función de la intensidad del ejercicio.



VT1: primer umbral ventilatorio; LT1: primer umbral láctico; MLSS: Máximo estado estable de lactato; OBLA: Lactacidemia fija de 4 milimoles; RCP: Punto de compensación respiratoria; VT2: segundo umbral ventilatorio; LT2: segundo umbral láctico; VO2max: consumo máximo de oxígeno.

1.1.2.4 Estudio clásico de los hitos fisiológicos y sus limitaciones

El estudio de los distintos umbrales ventilatorios y lácticos se suele realizar durante un test incremental en el laboratorio. En dicha prueba, el ciclista comienza a pedalear sobre un cicloergómetro a intensidades relativas bajas que se van incrementando progresivamente, ya sea de manera constante o escalonada. La prueba finaliza con la fatiga voluntaria del deportista, con la observación de la meseta de VO_{2max} o con la determinación de variables secundarias como la FC máxima teórica, el cociente respiratorio, una determinada lactacidemia o la percepción subjetiva del esfuerzo.

La utilización de procedimientos de laboratorio basados en análisis de gases para el estudio de los parámetros ventilatorios en poblaciones de deportistas de especialidades de resistencia tiene gran popularidad (Beltz et al., 2016). A pesar de ello, este tipo de procedimientos conllevan una serie de limitaciones: por un lado, requieren acceso a materiales específicos y personal cualificado requerido para el desarrollo de la prueba para los análisis. Por otro lado, el alto coste económico debe ser asumido por el deportista o su entorno. Además, el estudio debe realizarse en el laboratorio, aspecto que conlleva el desplazamiento al lugar de la valoración y con ello la posible alteración de la agenda de entrenamientos (Beltz et al., 2016). Por último, también debe subrayarse que los análisis de gases no están exentos de limitaciones propias de otros recursos: la determinación de los dos umbrales ventilatorios puede verse influenciada por los métodos utilizados para su establecimiento, la precisión y validez del instrumental utilizado y las posibles diferencias inter e intra observador (Poole et al., 2020).

Intentar establecer umbrales metabólicos característicos del ejercicio a intensidad constante mediante el uso de tests incrementales de intensidad variable conlleva una serie de limitaciones que no deben ser menospreciadas: durante un test incremental, el VO_2 y el VCO_2 no alcanzan un estado estable debido a los constantes cambios en la demanda de energía. Esto tendrá como consecuencia que el VO_2 medido a una determinada intensidad del ejercicio incremental será menor que el VO_2 medido a esa misma intensidad durante el ejercicio constante, con el consiguiente riesgo de sobreestimar la intensidad para un determinado VO_2. Esta limitación se puede paliar parcialmente con la utilización de estadíos y tests incrementales de mayor longitud, pero numerosos autores sugieren que incluso en estos casos es necesario realizar ajustes de verificación de los hitos fisiológicos detectados en el test incremental (Caen et al., 2020; Iannetta et al., 2019; Iannetta et al., 2020). La realización de dichos ajustes supone prolongar y complicar todavía más el protocolo de laboratorio, algo que puede entrar en contradicción con el contexto práctico de los estudios fisiológicos en los que en muchas ocasiones se cuenta con tiempo y protocolo delimitado.

La determinación del VO_{2max} se hace durante el test incremental en el que también se obtienen los umbrales ventilatorios. No obstante, esta técnica está sujeta a una serie de limitaciones: el VO_{2max} obtenido puede variar en función de la longitud del test y sus escalones, de la presencia de una meseta de VO_2 y de la utilización de medidas de verificación secundarias si la meseta no se visualiza (Jamnick et al., 2018). Además, algunos autores han sugerido que el VO_2 pico obtenido en el test incremental debería ser verificado con un intervalo a intensidad superior a la del último escalón completado, poco después de finalizar el protocolo incremental (Poole & Jones, 2017). Por otro lado, investigaciones recientes sugieren que las medidas indirectas comúnmente utilizadas para determinar la finalización de un test incremental, tales como la FC máxima teórica, la lactacidemia, el cociente respiratorio o la percepción subjetiva del esfuerzo, no deberían ser utilizados para ese fin por su gran variabilidad y escasa fiabilidad (Poole & Jones, 2017). Con todo ello, los tests incrementales comúnmente utilizados se complican todavía más y, o bien van asociados a una estancia todavía mayor en el laboratorio o bien directamente pueden requerir de dos visitas por parte del deportista en un intervalo de tiempo no muy amplio (Pettitt & Jamnick, 2017).

Al contrario de lo que sucedía con los hitos ventilatorios, la determinación de los umbrales lácticos y el estado estable de lactato puede realizarse fuera del laboratorio (Crotty et al., 2021). Esto tiene como consecuencia un menor requerimiento a nivel de material específico y personal, permitiendo la realización del estudio en el propio entorno de entrenamiento del deportista. No obstante, siguen existiendo costes añadidos tales como los del analizador de lactato, las propias tiras reactivas o las lancetas usadas para perforar el lóbulo de la oreja en el muestreo de sangre capilar. Se trata además de un proceso invasivo que requiere de medidas estrictas de higiene y un seguro frente a imprevistos (Beneke, Leithäuser, & Ochentel, 2011). Además, la determinación precisa del máximo estado estable de lactato requiere de varios días de testeo, con los inconvenientes que esto presenta para el deportista y entrenador (Płoszczyca et al., 2020). Debe tenerse en cuenta también la limitación propia de los analizadores de lactato portátiles: existe variabilidad entre distintos utensilios y pueden reportar valores de lactato superiores a los obtenidos con los analizadores de laboratorio, hecho que condicionaría mucho la determinación de métricas basadas en lactacidemias fijas (Crotty et al., 2021). Por todo lo anterior, aunque los tests basados en el análisis de lactato pueden resultar más convenientes que la medición de parámetros ventilatorios, también conllevan una serie de limitaciones que se deben tener en cuenta a la hora de programar este tipo de estudios.

A la hora de determinar la frecuencia idónea para el análisis de parámetros ventilatorios y lácticos en ciclistas se debe tener en cuenta que éstos son muy sensibles, dinámicos y reactivos al entrenamiento. Por ello, el monitoreo preciso del deportista puede requerir de visitas recurrentes al laboratorio con el fin de determinar correctamente su evolución fisiológica y el establecimiento de las zonas de trabajo durante la temporada (Seiler & Kjerland, 2006). Debido a las inconveniencias asociadas a los constantes desplazamientos al laboratorio, al coste de los análisis realizados y a las limitaciones técnicas propias de los estudios con gases y lactato, existe una necesidad real para poder estimar los hitos ventilatorios y lácticos de manera indirecta en el campo (Passfield, Hopker, Jobson, Friel, & Zabala, 2017). Esta alternativa permitiría reducir los costes temporales y económicos del seguimiento del deportista, así como protocolizar mejor los análisis al reducir las discrepancias intra e inter observador.

1.2 Uso de la potencia como alternativa a los estudios de laboratorio

Durante los últimos años, el progresivo abaratamiento y aumento de la disponibilidad de los potenciómetros ha permitido que ciclistas profesionales y aficionados puedan medir, comparar y analizar su rendimiento con una importante reducción de costes tanto monetarios como temporales. Las condiciones externas como el viento, la superficie de la carretera, la pendiente, la masa o el tamaño del ciclista tienen una gran influencia en las variables de rendimiento. La potencia es independiente a esas influencias externas y, por tanto, resulta mucho más apropiada para analizar el rendimiento que otros marcadores históricamente muy utilizados como la percepción subjetiva del esfuerzo, la velocidad o la FC (Passfield et al., 2017). Los estudios de laboratorio se caracterizan por el análisis de variables de carga interna (VO_2, lactacidemia, FC, etc) como respuesta a una determinada carga externa (W) que ha sido impuesta al deportista. La posibilidad de estimar los parámetros de carga interna a partir de los datos de potencia podría ayudar a trasladar análisis propios del laboratorio a un contexto mucho más cercano y accesible para el deportista. Dada su disponibilidad y facilidad de uso, se podría sugerir que el uso de medidores de potencia móviles puede representar una alternativa a las evaluaciones de laboratorio para la determinación de los principales hitos fisiológicos. Las principales aplicaciones prácticas derivadas del uso de potenciómetros podrían resumirse en 1) determinación del máximo estado estable metabólico; 2) determinación de la curva de potencia del deportista para predecir, comparar y monitorear el rendimiento y 3) monitoreo de los requerimientos de potencia de las competiciones.

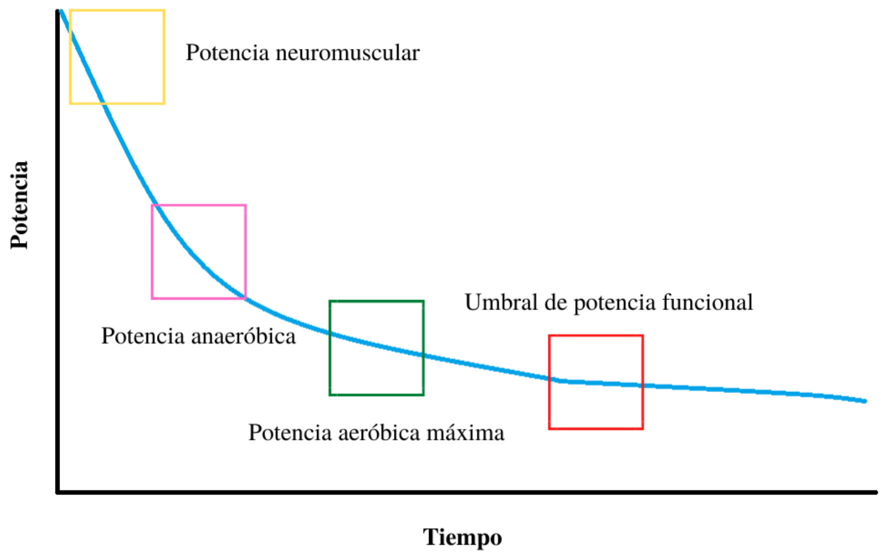
1.2.1 Umbral de potencia funcional (UPF)

Similarmente a lo que sucedía con los análisis basados en parámetros ventilatorios y lácticos, diversos científicos han intentado determinar el máximo estado estable metabólico a partir de los datos de potencia, concepto al que se le ha dado el nombre de umbral de potencia funcional (UPF). Se han propuesto diversos métodos de determinación del UPF: desde un test directo buscando conseguir la mayor producción de potencia durante un esfuerzo cercano a una hora hasta el análisis de la curva de potencia buscando su aplanamiento como representación del UPF (Borszcz et al., 2018; Borszcz et al., 2019). Más concretamente, Allen y Coggan (2019), proponen que el UPF de un ciclista se puede obtener tras restar un 5% a la potencia obtenida durante un intervalo máximo de 20 minutos de duración integrado en un protocolo de testeo que incluye diversas series. Teóricamente, la intensidad asociada al UPF debería estar cercana a la del MLSS. Diversos estudios han intentado verificar esta teoría y, aunque el tiempo al agotamiento del UPF sí aparenta ser el del máximo estado estable metabólico, la relación entre éste y otros parámetros ventilatorios y lácticos es variable a lo largo de la literatura (Borszcz et al., 2018; Inglis et al., 2019; Borszcz et al., 2019 & Pereira Costa, 2019). Actualmente, la localización exacta de la intensidad del UPF frente a la de otros hitos fisiológicos convencionales sigue siendo discutida.

1.2.2 Determinación de la curva de potencia

El seguimiento de los registros máximos de potencia para todo tipo de duraciones permite la elaboración de una curva de potencia de naturaleza hiperbólica. Esta curva basada en los mejores registros de competiciones y entrenamientos del ciclista no sólo permite comparar su rendimiento previo y actual sino también permite proyectar el rendimiento futuro y, si se ajusta al peso del ciclista, incluso aporta datos para comparar las prestaciones entre diferentes deportistas (Bell et al., 2017; Pinot & Grappe, 2010; Pinot & Grappe, 2011; Pinot & Grappe, 2015). Algunos autores han llegado a proponer una tabla clasificatoria de ciclistas acorde a sus récords de potencia en duraciones que se han identificado como representativas de estados metabólicos clave: 5 segundos para la potencia neuromuscular, 1 minuto para la potencia anaeróbica, 5 minutos para el VO_{2max} y el 95% de la potencia máxima de 20 minutos para el máximo estado estable metabólico (Allen & Coggan, 2019). No obstante, se trata de conceptos puramente teóricos y, hasta la fecha, no se ha comprobado el nivel de predictibilidad que ofrecen los mejores registros de potencia para determinar estados metabólicos clave en el deportista. La figura 5 representa una curva de potencia con la localización de las duraciones que representan los estados metabólicos clave.

Figura 5. Curva de potencia y localización de los estados metabólicos relevantes.



1.2.3 Análisis de datos de competición

La recuperación de los datos de potencia de las distintas competiciones permite conocer los requerimientos fisiológicos necesarios para tener éxito en las mismas y, consecuentemente, planificar el entrenamiento. En los últimos años, el estudio de los datos de potencia obtenidos por corredores que participan en diversas carreras ha permitido un estudio más detallado de las necesidades fisiológicas de las mismas. Así, el relieve de una carrera determina en gran medida la distribución del tiempo en las distintas zonas de entrenamiento (Sanders & Heijboer, 2019; Vogt, et al., 2006; Vogt et al., 2007). Más específicamente, las etapas de montaña se caracterizan por picos de potencia mayores en duraciones superiores a los 10 minutos. Las etapas llanas y quebradas se caracterizan por una producción de potencia media máxima más alta durante períodos más cortos (<2 min). Además, las carreras de un solo día tienden a tener una mayor intensidad y carga en comparación con las etapas dentro de las carreras de varios días (Sanders & van Erp, 2021). Por otro lado, el análisis de las carreras permite cuantificar las diferencias observadas en distintas categorías tanto de nivel, como de género (Sanders, van Erp, & de Koning, 2019; van Erp & Sanders, 2020). A pesar del creciente interés en este ámbito, todavía quedan grandes vacíos en el conocimiento como las características de los llamados "esfuerzos ganadores" o momentos cruciales de cada competición y la posibilidad de proyectar el rendimiento en una prueba en base a la curva de potencia de un deportista.

1.3 Factores de rendimiento en el ciclismo de carretera

El ciclismo de carretera es un deporte de resistencia cíclico y muy popular que se caracteriza por altas demandas de energía aeróbica y anaeróbica, grandes volúmenes de entrenamiento y competición y altos requerimientos cardiorrespiratorios (Bossi & Hopker, 2017). La literatura científica actual ha identificado un amplio número de factores de rendimiento que determinan el desempeño final del deportista en la disciplina y podrían ser clasificados en torno a cinco grandes grupos: anatómicos o estructurales, biomecánicos, psicológicos, técnico-tácticos y fisiológicos (Phillips & Hopkins, 2020). Además, a la hora de evaluar el rendimiento del ciclista no sólo se deben tener en cuenta estos factores sino también su coherencia con la especialidad del propio corredor, que necesitará destacar en ámbitos distintos en función de su rol (líder o gregario) y categoría (esprínter, lanzador, escalador, rodador, contrarrelojista o jefe de filas) (Coyle et al., 1991).

Los factores de rendimiento anatómicos o estructurales variarán en función de la tipología del corredor. Estudios previos han descrito grandes diferencias entre diversas clases de corredores, con esprínters y rodadores caracterizados por estaturas y masas musculares más elevadas que los escaladores y jefes de fila (Baker & Reiser, 2017). En general, los ciclistas de carretera se caracterizan por índices de masa corporal, pesos y tasas de grasa reducidos (Foley, Bird, & White, 1989; Muros et al., 2019). Debido a que muchos desenlaces de carreras ocurren tras ascensiones más o menos prolongadas, no sólo los escaladores o jefes de filas sino también los esprínters están interesados en optimizar su ratio potencia/peso con el fin de llegar con opciones de victoria a las últimas fases de las carreras (Mujika & Padilla, 2001). También debería considerarse que el somatotipo del corredor influencia su área frontal, aspecto aerodinámico de relevancia a la hora de rendir en el llano o eventos contrarreloj. En estos casos, los corredores pequeños que sepan mantener una elevada potencia en el llano se verán beneficiados por su propia anatomía corporal (Peterman et al., 2015).

En cuanto a los factores de rendimiento biomecánicos, la postura del ciclista tanto sobre la bicicleta de ruta como la de contrarreloj influencian su área frontal y coeficiente aerodinámico, determinando con ello el rendimiento en el llano (Peterman et al., 2015). Otro aspecto destacable es la cadencia libremente elegida por el ciclista, aspecto que puede condicionar el tipo de fibra muscular utilizada predominantemente durante un determinado esfuerzo (Bertucci et al., 2005; Castronovo et al., 2013; Whitty et al., 2009). Finalmente, debe ser tenida muy en cuenta la calidad del pedaleo, elemento que determina la potencia absorbida y liberada durante el mismo, y con ello la potencia que va dirigida finalmente al desplazamiento de la bicicleta (Cannon, Kolkhorst, & Cipriani, 2007).

Los factores psicológicos, aunque menos estudiados, también suponen una importante aportación para el éxito final del ciclista. Las características propias de la disciplina (exposición a las inclemencias del tiempo, elevado volumen de entrenamiento, acumulación de esfuerzos) determinan que es deseable que el deportista cuente con determinadas características psicológicas que garanticen el aumento de las posibilidades de éxito. Así, estudios previos han determinado que los ciclistas de carretera se caracterizan por elevados niveles de motivación, gran manejo del estrés y por su capacidad de utilizar recursos mentales así como analizar su propio rendimiento (Olmedilla et al., 2018; Spindler et al., 2018).

En relación con los factores técnico-tácticos, debe ser tenida en cuenta la peculiaridad de la propia actividad, la cual es considerada un deporte de equipo en el que un solo individuo consigue la victoria. Por tanto, las decisiones estratégicas tomadas tanto por el corredor como por el director del equipo influencian el resultado final de la competición. En relación con esto, un reciente meta-análisis identificó cuatro claros campos de estudio predominantes: la influencia de la gestión del ritmo en el rendimiento, el rol de la utilización de distintos horarios de salida en una contrarreloj y su efecto sobre el resultado final, la evaluación de los coeficientes aerodinámicos en las persecuciones por equipos y la aplicación de video análisis para situaciones de carrera determinadas (Cesanelli & Indaburu, 2020). Por otro lado, la técnica del propio corredor resulta fundamental para la obtención de resultados: la gestión correcta de los descensos, así como un hábil manejo dentro del pelotón permiten reducir el riesgo de caídas e incidencias además de permitir al corredor estar en la cabeza de carrera en los momentos determinantes de la misma (Raya, 2015).

Los factores de rendimiento fisiológicos han sido históricamente los más estudiados dentro del deporte del ciclismo. Entre ellos, podemos distinguir aquellos que envuelven las adaptaciones centrales y periféricas. Si bien las adaptaciones de tipo central se han considerado esenciales y predictivas del rendimiento en deportes de resistencia, en la última década un número cada vez mayor de estudios han puesto sobre la mesa la relevancia de las adaptaciones periféricas en el ciclismo de carretera. Así, una revisión sobre la materia destacó los factores de rendimiento fisiológicos que mejor predicen el desempeño de los ciclistas de carretera: potencia en el umbral de lactato y en el MLSS, ratio potencia/peso superior a los 5.5 W/kg, porcentaje de fibras tipo I en el vasto lateral y potencia pico durante un test incremental (Faria et al., 2005).

1.4 Objetivos

1.4.1 Objetivo general

Establecer la utilidad de los datos de potencia como alternativa a los datos de laboratorio para el análisis del rendimiento en el ciclismo de carretera.

1.4.2 Objetivos específicos

Objetivo 1: Recopilar y revisar la evidencia científica producida hasta la fecha en torno a la utilización de los datos de potencia para el análisis del rendimiento en el ciclismo de carretera.

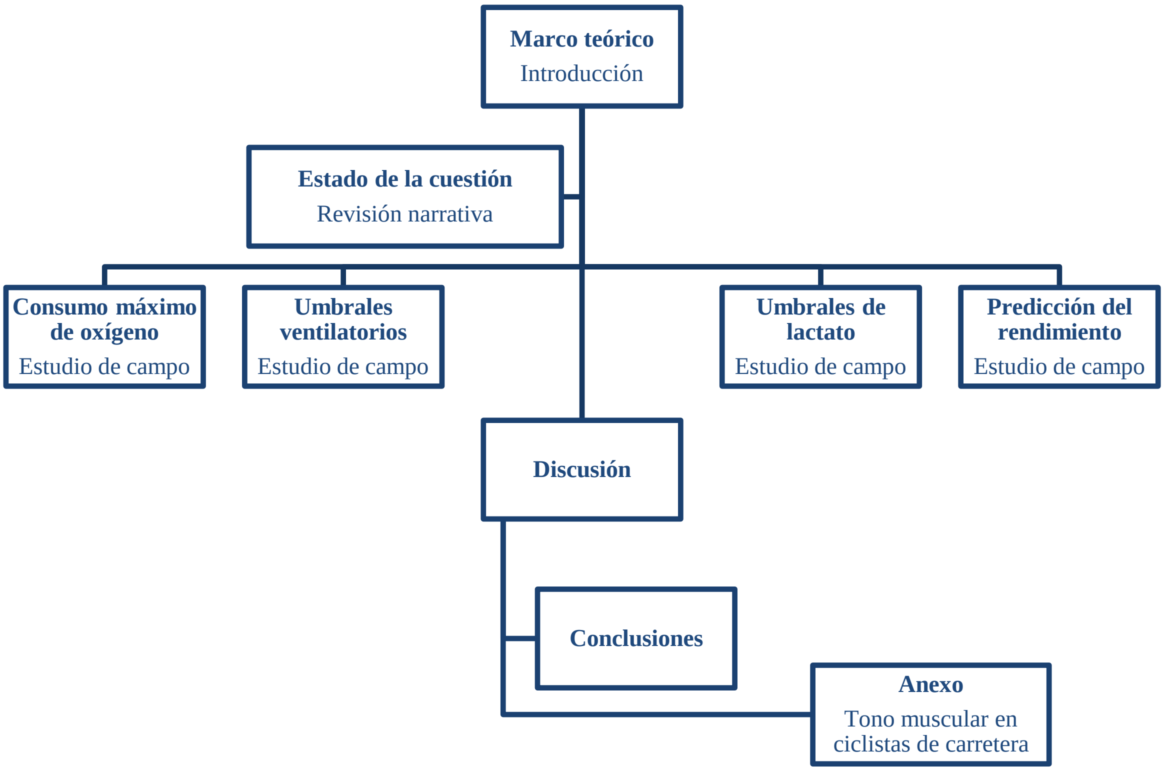
Objetivo 2: Determinar la relación existente entre el VO_{2max} obtenido en un test incremental en el laboratorio y el calculado a través de una estimación basada en datos de potencia obtenidos a través de un test de campo.

Objetivo 3: Estudiar la relación existente entre la intensidad del umbral de potencia funcional y los umbrales ventilatorios.

Objetivo 4: Determinar la relación existente entre el umbral de potencia funcional y los umbrales de lactato.

Objetivo 5: Estudiar la idoneidad de los datos de potencia para la predicción del rendimiento en un evento ciclista.

1.5 Estructura de la tesis



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2. Análisis de potencia en ciclismo de carretera: revisión narrativa

Power assessment in road cycling: a narrative review

Abstract: Nowadays, the evaluation of physiological characteristics and load training quantification in road cycling is being performed through several methods, but the scientific evidence behind these tools is scarce and often contradictory. The aim of this paper is to review the literature related to power profiling, functional threshold testing and performance assessment based on power meter data. A literature search was conducted following Preferred Reporting Items for Review Statement (PRISMA) on the topic of {"*cyclist*" OR "*cycling*" AND "*functional threshold*" OR "*power meter*"}. The reviewed evidence provided important insights regarding power meter based training: a) functional threshold testing is closely related to laboratory markers of steady state; b) the 20-minute protocol represents the most researched option for functional threshold testing although shorter durations may be used if verified on an individual basis; c) power profiling obtained through recovery of record power outputs allows the categorization and assessment of the cyclist's fitness level and; d) power meters represent an alternative to laboratory tests for the assessment of the relationship between power output and cadence. This review elucidates the increasing amount of studies performed, highlighting the opportunity for expanding knowledge that power meters have brought in road cycling field.

Keywords: *road cycling, power meter, endurance, training, performance assessment*

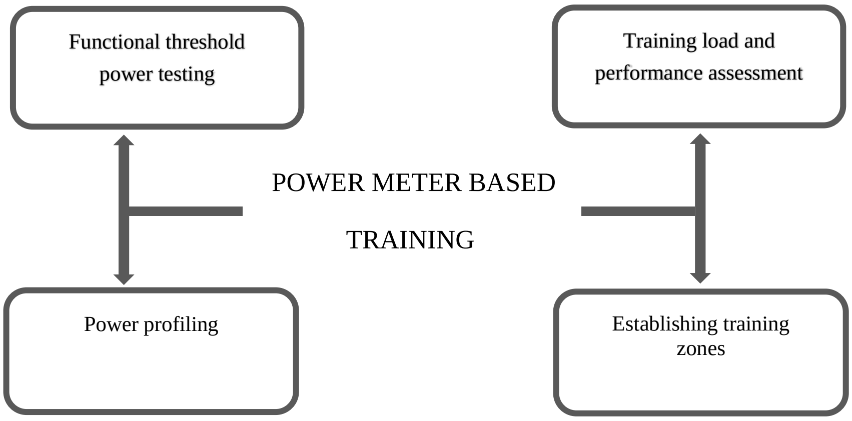
1. Introduction

Road cycling is an extremely demanding endurance sport characterized by its cyclic nature, large training volumes and high intensities [1] The activity is composed of several different disciplines with clear physiological differences according to the typology of the cyclist and the particularities of the event [2] As a consequence, different types of riders specialized in specific events and efforts have appeared: time trialists [3-4], sprinters [5] or grand tour riders [6] among others.

These differences have implications for the evaluation of training characteristics and load quantification, which are currently performed through several laboratory and field methods [7-8]. Among the field methods, subjective assessments such as ratings of perceived exertion stand out due to their easy implementation. Previous research has shown that such methods demonstrate moderate to very large differences compared to heart rate monitoring [7,9-13]. Heart rate-based assessments are also linked to several setbacks such as underestimation of neuromuscular and anaerobic efforts, delayed response to the stimuli and difficulties for precise assessment of intermittent efforts[14-16]. As for laboratory methods, measurements of oxygen uptake and blood lactate concentrations are normally performed. Although these measurements are precise and reliable [17], they are also linked to several limitations such as the reliance on expensive equipment and the need for a specific setting at a particular time [18]. Therefore, laboratory-based methods are inadequate for measuring performance and training load on a day-by-day basis. Mobile power meters (Mpm), contrary to heart rate monitors or subjective scales, measure workload directly and not only a physiological response to the effort [8,19]. Furthermore, the anaerobic threshold and VO_{2max}, two of the most important laboratory markers, can be calculated from power output (PO) during field training sessions [4,20]. Mpm accuracy and precision is generally high [21-23] and these tools may represent an interesting alternative for training load quantification given their ability to provide an objective assessment of anaerobic, neuromuscular and intermittent efforts.

Among the main practical applications of Mpm stands out the functional threshold power (FTP) testing proposed by Allen and Coggan. The result obtained from subtracting 5% of the mean PO sustained during a 20-minute time-trial is, according to the authors, the maximal PO which can be maintained by the cyclist in a quasi-steady state [19,24-27]. FTP is also used as a reference for establishing seven different training zones and, additionally, the testing protocol provides information about the riders' power profile, which can help in their classification according to their strengths and weaknesses [28-29]. Figure 1 summarizes the main practical applications of Mpm based training.

Figure 1: Main potential practical applications of data obtained through power meters



Mpm based assessments integrate both an objective measure of the work performed and the individual physiological characteristics, two elements that have been suggested as indispensable for the correct quantification of training load in road cycling [30]. Although the FTP test, the training zones derived from its determination and the power profile charts are being commonly used by athletes and coaches, the scientific evidence behind these tools is scarce and often contradictory. Consequently, the following narrative review aims to shed light on the scientific background behind the main practical applications of Mpm in road cycling.

2. Methods

2.1.Information sources

A computer-based scientific literature search was completed from inception to March 31th 2020, using the following information sources: Medline (PubMed), Web of Science (WOS), the Cochrane Collaboration Database, Cochrane Library, Evidence Database

(PEDro), Evidence Based Medicine (EBM) Search review, National Guidelines, EMBASE, Scopus and Google Scholar system. To obtain an overview of the methodologies used to study FTP, power profiling and power-based training zones, a broad search for topics relating to cycling and Mpm using the keyword: *"cyclist", "cycling", "functional threshold" and "power meter*" with Boolean operators such as: "AND" or "OR". Furthermore, this narrative review was conducted in accordance with the Preferred Reporting Items for Review Statement (PRISMA) guidelines [31]

2.2.Study Inclusion Criteria

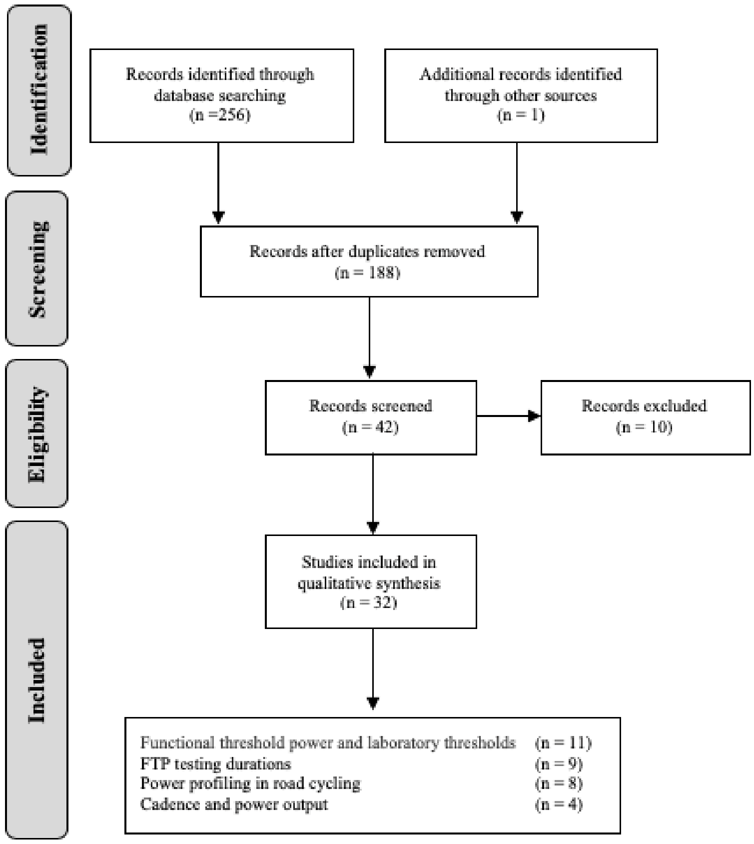
Two reviewers independently examined all the titles and abstracts of all publications and determined the relevance of the publication for inclusion. The criteria for allocations in the articles were satisfied. A manuscript's full-text was obtained to ascertain if the publication satisfied the inclusion criteria. In addition, the reference sections of the selected articles were searched to identify other relevant articles. When considering final inclusion in this review, each paper's relevance to the following question was considered: Does this document add to the field of Mpm based cycling training and performance assessment?

Following an initial full text review, 42 out of the original 256 articles were deemed directly relevant to the topic and therefore included for detailed reading. Using these criteria, 32 scientific papers with clear methodologies were selected for this review together with one relevant book, which was also kept in the database and used to connect this paper's focus on empirical methods with the practical discourse on FTP and Mpm data

2.3.Study Exclusion Criteria

Other cycling disciplines were not considered and duplicated articles were deleted. On the other hand, abstracts, non-peer reviewed papers and book chapters were excluded.

Figure 2. Flow diagram of study selection



3. Review of the literature

3.1. Relationship between Functional Threshold Power and laboratory thresholds

Ventilatory and lactate thresholds can be currently obtained through different methods during a graded exercise test. Ventilatory threshold (VT) [32] and respiratory compensation point (RCP) [33] are commonly calculated from oxygen uptake data. There is also a broad range of lactate thresholds (LT) which respond to different concepts and can be obtained through several different testing protocols: individual anaerobic threshold (IAT) [34], maximal lactate steady state (MLSS) [35], fixed blood lactate concentrations of 2 and 4 mmol/L, initial rises of 1 mmol/L, Dmax [36] and modified Dmax [37] methods.

The evidence regarding the true relationship between FTP and this broad range of laboratory-set thresholds is scarce and contradictory. It has been verified that FTP obtained from a 20’ test can be sustained for long time periods (50-60 minutes) [38-39], an estimation that approaches the quasi-steady state proposed by Allen and Coggan. Therefore, out of all the methods for establishing the laboratory thresholds, the MLSS and the RCP should theoretically be linked to the FTP as both refer to stable states that can be sustained over time [40]. These relationships have been previously tested and the correlations were nearly perfect for both RCP (r = 0.97) and MLSS (r = 0.91), although the intensity at which MLSS was represented differed as much as 7% from FTP [42]. Furthermore, the relationship changed depending the cyclists’ level, since the well-trained group showed a higher association (r = 0.94) than the trained group (r = 0.91) [28,42-43]. Similar findings have been obtained in another study in which FTP and LT were closely linked in trained cyclists but not in recreational cyclists [24]. The PO obtained from FTP 20’ testing doesn’t seem to correlate with all the other LT methods [24,26-27], except for fixed blood lactate concentrations of 4.0 mmol/L (r = 0.88, $p < 0.001$) [43]. On the other hand, another FTP testing duration has been attempted in several scientific studies. Carmichael and Rutberg [44] proposed an 8-minute FTP estimation test, where 90% of the mean PO was used for calculating the functional threshold. As happened with the 20’ FTP test, a meaningful relationship was only established when LT was determined as the onset of blood lactate at 4.0 mmol/L, although moderate correlations were obtained for lactate thresholds obtained as initial rise of 1.00 mmol/L, Dmax and modified Dmax (r = 0.61 - 0.82) [25,45-46]. Table 1 summarizes the most important aspects of the studies included in this section of the review.

From the reviewed studies, the protocol proposed by Allen and Coggan has been most used for establishing FTP, and high correlations between FTP obtained through this method and several laboratory tests such as RCP and MLSS have been observed. However, the existence of high levels of inter-individual variability could influence the obtained values. Although various studies have proven a relationship between FTP and LT determined as the onset of blood lactate at 4.0 mmol/L, it is well known that establishing LT at fixed blood lactate levels does not take into account the considerable inter-individual differences in lactate metabolism and it may overestimate or underestimate the MLSS, which shows great variability among individuals (from 2-8 mmol/L) [47]. Therefore, this finding remains anecdotal as relying on fixed values for determining the anaerobic threshold is no longer accepted in the practical field [48]. On the other hand, the fitness level could influence the relationship between FTP and laboratory thresholds. The reviewed studies have used samples characterized by wide ranges of fitness levels (VO_{2max} from 46 to 75 ml/kg/min^{-1}), differences that could have an influence on the relationship between FTP and laboratory markers. Finally, it has been suggested that the test is more reliable in cyclists with higher levels of fitness, a finding that should be further explored in future studies.

Table 1: Summary of the research attempting to study the relationship between functional and laboratory-set thresholds

Study	Sample	FTP estimation method	Laboratory threshold estimation method	Results	Practical application
Borszcz et al., 2018	23 trained male cyclists (VO_{2max} 59.4±5.9 ml/kg/min)	95% of 20-minute maximal power output and 60-minute mean power output.	1.5mmol/L above the point of minimum ratio between La and work rate.	Large to very large correlations were found between LT and FTP20 (0.61) and between LT and FTP60 (0.76) for PO.	Both tests are more related to LT than 8-minute tests. FTP and LT should not be used interchangeably unless tested on an individual basis
Borszcz et al., 2019	7 trained (VO_{2max} 55-64.9 ml/kg/min) and 8 well trained (VO_{2max} 65-71 ml/kg/min) cyclists.	95% of 20-minute maximal power output	Highest exercise intensity in which La did not show an increase of >1 mmol/L.	r = 0.91 between FTP and LT. Well-trained group showed a higher association with the PO measures (r = 0.94) than the trained group (r = 0.91).	FTP can be used as a non-invasive and practical alternative for estimating LT.
Bossi et al., 2017	15 trained cyclists ($VO2_{max}$ 56.1±7.7 ml/kg/min).	95% of 20-minute maximal power output	VT and RCP.	r = 0.80 between FTP (w/kg) and RCP. r = 0. 59 between FTP and VT.	FTP determined from a 20-min test is strongly related to laboratory variables.
Calaine et al., 2019	18 competitive cyclists	95% of 20-minute maximal power output	MLSS	PO at MLSS represents 93.1% of PO at FTP.	PO at FTP is higher than PO at MLSS.
Gavin et al., 2012	7 trained male competitive cyclists (VO_{2max} = 65.3 ± 1.6 ml/kg/min)	90% of 8-minute maximal power output	1 mmol/L or greater rise in blood La and blood La of 4.0 mmol/L.	PO at estimated FTP from the 8-minute FTP was significantly greater than the PO at LTD1 but not different from the PO at LT4.0.	FTP was only equivalent to LT at 4.0 mmol/L.
Jeffries et al., 2019	20 competitive male cyclists	95% of 20-minute maximal power output	Fixed blood La concentration 4.0 mmol/L, Dmax and modified Dmax.	FTP was strongly correlated (r = 0.88, p < 0.001) with the PO associated with a fixed blood La concentration 4.0 mmol/L but no association was found with other measures.	FTP was only associated to LT at 4.0 mmol/L.
Klika et al., 2007	24 recreational cyclists (VO_{2max} 46.2 ml/kg/min)	90% of 8-minute maximal power output.	Power at which blood La increased 1 mmol/L above baseline.	FTP was approximately 7.5% higher than LT measured under laboratory conditions.	Adjustments are needed when using FTP and LT interchangeably.
McGrath et al., 2019	19 highly trained cyclists and triathletes (VO_{2max} 66.3±5.5 ml/kg/min)	95% of 20-minute power output	Dmax	89% of athletes sustained FTP during 60-minutes. r2 = 0.89 between Dmax and FTP.	FTP represents a quasi-steady state that can be sustained for one hour.
Nimmerichter et al., 2010	15 competitive male cyclists (VO_{2max} 65±4 ml/kg/min)	20 and 4-minute maximal power output.	VT; RCP, nonlinear increases in La vs power output.	PO during the 20 min time-trial correlated with PO at the second lactate turn point and the RCP.	PO during 20 min time-trial has acceptable accuracy to determine laboratory markers.
Sanders et al., 2017	19 well-trained road cyclists (VO_{2max} 64 ± 4 ml/kg/min).	90% of 8-minute maximal power output.	4 mmol/L, initial rise of 1 mmol/L above baseline, Dmax and modified Dmax.	FTP very largely different than Dmax, largely different than PO at initial lactate rise of 1 mmol/L and moderately different than PO at 4 mmol/L and mDmax.	The 8-minute FTP test is recommended as a tool for endurance assessment but cannot be used interchangeably with LT.
Valenzuela et al., 2018	11 recreational (peak power output <4.5w/kg) and 9 trained (peak power output >4.5w/kg) cyclists.	95% of 20-minute maximal power output	Dmax.	Strong correlation between FTP and LT (r = .95; P < .0001) but FTP was significantly lower (P = .0004) in recreational cyclists.	FTP can be used for the assessment of endurance fitness. However, it may underestimate LT in recreational cyclists.

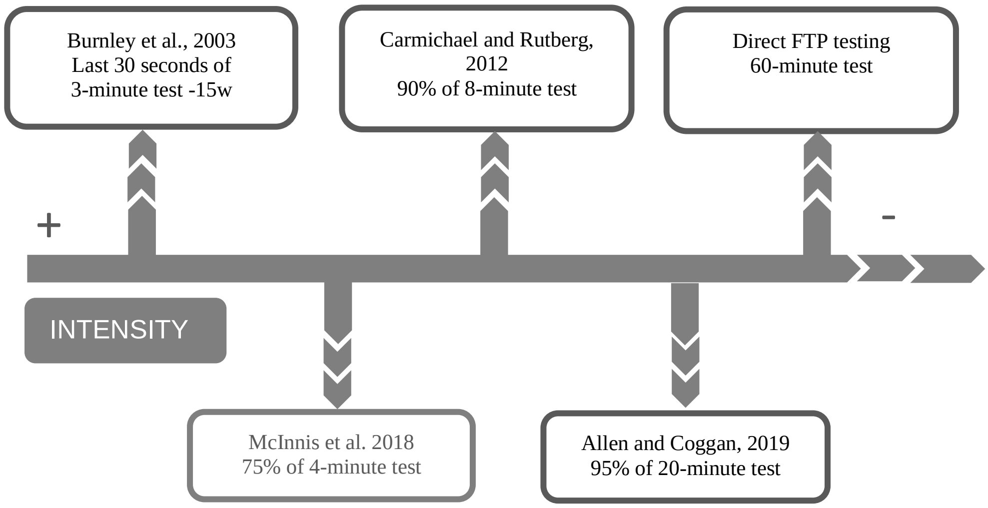
FTP=Functional Threshold Power; PO= Power Output; LT=Lactate Threshold; VT= Ventilatory Threshold; RCP= Respiratory Compensation Point; MLSS= Maximal Lactate Stable State; La=Lactate

3.2.FTP testing durations

As stated in the previous section, FTP obtained through Allen and Coggan's method [19] is very highly correlated to steady-state physiological concepts such as both MLSS [28] and RCP [42-43]. Despite that, this testing duration may have some setbacks: experience and pacing strategy play an important role in long time-trial like efforts [49-50] and the results of the test seem to be strongly influenced by previous familiarization [51], especially in inexperienced athletes. As the FTP is, per definition, a quasi-steady state which relies mainly on aerobic metabolism, it could be suggested that almost any steady state time-trial effort of sufficient duration would be related to this threshold [52]. Consequently, several authors have suggested shorter alternatives for testing FTP.

Carmichael and Rutberg [44] proposed an 8-minute test for estimating FTP, which doesn't seem related to any laboratory-set threshold except for fixed blood lactate concentration of 4 mmol/L [26,45-46]. Furthermore, to date, it has not been confirmed whether 90% of the 8-minute PO equals 95% of the 20-minute PO. It is well known that maximal PO obtained during a graded exercise test accurately predicts FTP [52] and as much as 91% of PO variation in a 20-minute test can be explained by peak oxygen uptake [43]. Accordingly, several even shorter durations have been proposed for FTP testing: 4-minute PO seems to be very strongly correlated to 20- and 60-minute PO (r = 0.92-0.95, $p < 0.001$) and could represent 75% of the maximal PO that can be sustained during one hour [53]. Contrarily to what is suggested in the standard protocol, this study showed that 60-minute PO represented 90% and not 95% of 20-minute PO, a difference that could be explained by a slightly easier warm-up than what is suggested by Allen and Coggan. It has also been proposed that subtracting 15 watts to the mean PO obtained in the last 30 seconds of a 3-minute all out test results in a steady state that can be maintained with stable VO_2 and blood lactate levels, although no assessment of 20-minute PO was performed in this case. These results, despite being promising, could only be verified in 60% of all tested subjects [54] and therefore caution is required when attempting these protocols on a group basis without previous verifications. Figure 2 represents a summary of the different durations and intensities proposed for establishing FTP.

Figure 3: Main FTP testing durations and intensities



As described in this section, different FTP testing durations have been evaluated in previous scientific research. The protocol proposed by Allen and Coggan allows the determination of a steady-state PO that is commonly linked to several laboratory markers such as MLSS and RCP. Shorter tests may represent a promising alternative especially for unexperienced athletes due to their easy implementation and limited duration. However, current evidence regarding these alternatives is still scarce and therefore further studies need to clarify whether shorter protocols can be used interchangeably with the Allen and Coggan's test.

3.3. Power profiling in road cycling

The power profiling first proposed by Allen and Coggan [19] has been used during the last decade in order to objectively quantify performances of different cyclists and to categorize riders according to their strengths and weaknesses. This ecologically valid assessment of power producing capacity over cycling specific durations is a useful tool for quantifying elements of cycling specific performance in competitive and recreational cyclists [55]. It has been established in competitive, elite and professional cyclists that the power profile obtained in the laboratory can successfully match values obtained by recovering training and competition data during full cycling seasons [29-30,55]. This signature of the cyclists' physical ability is based on a hyperbolic relation between the record PO over different durations (1 second to 4 hours) and is normally used to compare data between different classes of riders: among professional riders, sprinters have the highest PO for 1 to 5 seconds (up to 20 W/kg), climbers present the highest PO for 5 to 60 minutes (5.5 to 6.5 W/kg) and flat specialists present high PO for durations up to three hours (over 4 W/kg) [29-30]. Finally, the power profile of grand tour riders shows high PO throughout the entire curve: values of 18.1-20.4 W/kg for 1 to 5 seconds; 7.2-5.7 W/kg for 5 to 60 minutes and almost 5 W/kg for 3 hours have been previously reported in the literature [56].

Interestingly, the power profile of riders who specialize in a particular type of event can be matched with data obtained through analysis of different types of races such as time-trials [57], different grand tour stages [58] or even cycling sportive events [59]. The opportunity to analyse the power requirements that characterize a specific event and then compare them to the strengths and weaknesses of the rider should not be overlooked due to its potential applications in the practical field.

Finally, power profiling has allowed researchers and coaches to objectively track riders' levels and changes in performance without the need to use expensive laboratory equipment to assess fitness through cardiorespiratory values such as VO_{2max} or VT/LT. Besides the practical field, scientists have also started to acknowledge this potential way of assessing performance and nowadays it is increasingly common to find studies in which the participants' fitness level or changes in performance are measured in W/kg [25,59-61].

3.4.Cadence and power output

The opportunity to objectively assess intensity in cycling has brought attention to new details such as the optimal cadence associated to a specific PO. This new possibility for implementing field tests seems important, especially when considering the important setbacks associated with studying power related to cadence in a laboratory setting: it has been established that crank torque profiles in the ergometer are significantly different and generate a higher perceived exertion compared with road cycling conditions [62]. Furthermore, the crank torque profile varies substantially according to the terrain, a conditioning factor that cannot be recreated in a laboratory setting [63]. It should also be remarked that self-selected cadence is normally higher in the laboratory setting compared with road conditions [55] and imposing a cadence can modify the amount of work that a cyclist can complete above his FTP [64].

Taking all of the previous into account, the importance of obtaining field power and cadence data should be emphasized. Previous evidence suggests that higher PO is linked to higher self-selected cadence [65] although this relationship could be modified through specific training [66], with low cadence intervals improving performance in time-trial like efforts and high cadence intervals increasing the self-selected cadence. At this moment, it remains unknown whether there is a relationship between FTP and self-selected or more efficient cadence.

4. Conclusions

Power meter-based training has come to stay in the field of road cycling. The opportunity to objectively assess performance, categorize riders according to their fitness and track training load accurately cannot be overlooked by cyclists, coaches and scientists. The summary of the current evidence puts light on several aspects that were, until now, followed more by conviction than science.

From the evidence presented in this review, it could be suggested that FTP is closely related to but does not necessarily represent several laboratory markers of steady state such as RCP and MLSS. This relationship, however, is not always sustained on a one by one basis. Therefore, although FTP can be used for precise tracking changes in performance, it shouldn't be used interchangeably with any laboratory marker until this relationship has been proved individually. Consequently, this new "threshold" represents a parallel but not equal concept to laboratory set thresholds. Although several shorter protocols have been suggested, the lack of scientific background regarding their true validity must be considered and, as of now, the 20-minute protocol represents the most researched option for testing FTP. Power profiling obtained through recovery of record PO for different durations from series of training and competition data allows the categorization and assessment of the cyclist's fitness level without the need to perform complex laboratory tests. Riders of different levels are being currently assessed through this method and soon it will probably become the preferred tool for categorizing cyclists.

Mpm represent a revolutionary tool for assessing the relationship between cadence and power in the field. Up until the last decade, this relationship could only be studied in a laboratory setting, a context in which cadence is dramatically altered. As evidenced by the increasing amount of studies performed during the last decade, the coaching and scientific fields are not overlooking the opportunity for expanding knowledge that Mpm have brought.

Author Contribution: All authors conceived the research idea and the framework of this study. All authors have read and approved the final manuscript.

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3. Test de potencia de 5 minutos para predecir el VO_{2max} en ciclistas de carretera

Five-minute power-based test to predict VO_{2max} in road cycling

Abstract:

Purpose:

To examine the ability of a multivariate model to predict maximal oxygen consumption (VO_{2max}) using performance data from a five-minute maximal test (5MT).

Methods:

Forty-six road cyclists (age 38 ± 9 years; height 177 ± 9 cm; weight 71.4 ± 8.6kg and VO_{2max} 61.13 ± 9.05 ml/kg/min) completed a graded exercise test (GXT) to assess VO_{2max} and power output. After a 72h rest they performed a test that included a five-minute maximal bout. Performance variables in each test were modelled in two independent equations using Bayesian general linear regressions to predict VO_{2max}. Stepwise selection was then used to identify the minimal subset of parameters with the best predictive power for each model.

Results:

Five-minute relative power output (RPO) was the best explanatory variable to predict VO_{2max} in the model from the GXT (R^2 95% CI: 0.81 to 0.88) and when using data from the 5MT (R^2 95% CI: 0.61 to 0.77). Accordingly, VO_{2max} could be predicted with a 5MT using the equation VO_{2max} = 16.6 + (8.87 * 5-min RPO).

Conclusions:

Road cycling VO_{2max} can be predicted in cyclists through a single-variable equation that includes relative power obtained during a 5MT. Coaches, cyclists, and scientists may benefit from the reduction of laboratory assessments performed on the athlete due to this finding.

Keywords: Endurance; power output; power meter; maximal oxygen consumption; training

INTRODUCTION

Over the last years, multiple performance factors have been identified in road cycling[1]. Among the physiological determinants of performance, maximal oxygen consumption (VO_{2max}) adjusted to body mass can be highlighted as a key parameter of cardiorespiratory fitness[2]. Normally, gas exchange measurements during graded exercise tests (GXT) are used to assess VO_{2max} in cyclists. Although these determinations allow direct oxygen and carbon dioxide calculations, they also present several setbacks: several different GXT protocol and step durations have been proposed in the past. However, previous research highlights that the use of different GXT protocols may yield varying VO_{2max} results[3–5]. Additionally, VO_{2max} results may also vary for several other reasons. For instance, GXT length could lead less motivated individuals to stop exercising before the VO_{2max} intensity is reached[4]. Also, different exercise modalities may render different VO_{2max} results. Lastly, reaching the VO_2 plateau is necessary for VO_{2max} determination through GXT, which is not always achieved in these tests[6,7]. In these cases, relying on secondary criteria or verification tests further complicates the assessment[4] and puts the spotlight on alternative VO_{2max} assessment methods.

The interest in self-paced short duration maximal efforts for the determination of VO_{2max} has risen in the last years. The estimation of VO_{2max} from these types of efforts has a relevant physiological basis: VO_{2max} values obtained during a GXT can be reached in many cases during the first two minutes of a maximal exercise bout, with four to five minute intervals showing VO_2 decrements in the last part of the effort[8–10]. This has been confirmed by studies assessing time to exhaustion at the VO_{2max} intensity in several endurance sports such as swimming, cycling and running, in which times to exhaustion of 3 to 5 minutes are commonly reported[11,12]. If VO_{2max} can be attained during a short maximal effort, this kind of intervals could be used to predict this important cardiorespiratory fitness determining factor: several studies have shown that 3 and 5-minute maximal intervals can predict VO_{2max} attained during a GXT in several populations such as trained and untrained adults and adolescents[13–15]. Although these results seem promising, they should not be extrapolated to specific performance groups such as road cyclists, as previous studies have shown that VO_2 behavior during a short interval may vary depending on the sport discipline, fitness status and effort duration [11]. To date, the usefulness of a short maximal interval for the prediction of VO_{2max} in the road cycling population has not been established.

In the last years, the possibility of assessing power output in the field has been provided by the exponential rise in the use of power meters among professional and amateur cyclists. These user-friendly tools allow the collection of real-time power data with reduced associated costs[16]. The possibility of assessing power output in the field has brought interest into the indirect measurement of several ventilatory and lactate landmarks[17]. In order to sustain a specific power output, energy needs to be regenerated at a rate that matches demand, a process that depends on the body's ability to supply oxygen to the muscle[18]. Previous research has shown linear VO_2 responses to increasing power output demands during GXT until the lactate threshold is reached, with non-linear increases afterwards[19–21]. The VO_2 behaviour during supra-threshold exercise is related to the cyclists' performance level and predominance of fiber type, with type IIX fibers associated to higher VO_2 excess at higher power outputs[22]. As the relationship between VO_2 and power output varies at different exercise intensities, a short supramaximal exercise bout could represent an opportunity to predict VO_{2max} through the assessment of the power output. The direct link between VO_2 and power output could represent an opportunity to predict VO_{2max} through the assessment of the power output measured during a short maximal exercise bout that could be easily implemented in a field setting.

Given the easy accessibility to power output measurement by cyclists, coaches and scientists and considering the inconveniences related to assessing VO_{2max} during a GXT, we hypothesized that a five-minute interval could be used to predict VO_{2max} obtained through gas exchange methods in a GXT. Consequently, the objective of the present study was to examine the ability of a multivariate model to predict VO_{2max} using performance data from a five-minute maximal test (5MT).

METHODS

Participants

We recruited forty-six road cyclists for the study (age 38 ± 9 years; height 177 ± 9 cm; body mass 71.4 ± 8.6 kg; body mass index 22.69 ± 2.23 kg/m^2; fat mass 11.1 ± 4.5%; VO_{2max} 61.13 ± 9.05 ml/kg/min). The inclusion criteria were a) current owner of a cycling license: World Tour, Elite/U23, Masters or recreational; b) absence of surgical procedures and injuries in the six months prior to the study c) absence of drug use in the six months prior to the study. The sample was composed by recreationally trained (n = 14), trained (n = 11), well trained (n = 10) and professional (n = 11) cyclists according to previous guidelines for the classification of endurance athletes[23]. After being informed of the benefits and potential risks of the investigation, each participant completed a health-screening questionnaire and provided written informed consent prior to participation in the study. The study followed the ethical guidelines of the 2013 Declaration of Helsinki and received approval from the Research Ethics Committee of the autonomous region of Aragon, Spain (PI19/447).

Experimental design

Participants completed the study on two separate days with a 72h rest in between. On the first day, we assessed the body composition of all cyclists through the electrical impedance method (BC-602, Tanita Co., Tokyo, Japan) in the morning hours. We measured height with a SECA 214 stadiometer (Seca., Hamburg, Germany), which is graduated up to 1 mm. After the body composition assessment, participants performed a GXT based on previous protocols[24]. The GXT commenced at a workload of 150W, with 25W increments every three minutes until exhaustion. In all cases, a five-minute warm-up at 100 W was allowed before commencement of the test. The assessment ended after a plateau of the VO_2 curve was reached or, when not seen, at voluntary fatigue when 100% of estimated HR_{max}, a Rate of Perceived Exertion (RPE) of ≥18 and respiratory exchange ratio of ≥1.15 were attained[5]. We asked the participants to totally refrain from exercise until the next assessment.

After a three-day rest, participants returned to the laboratory for the second assessment, which was based on the testing protocol suggested by Coggan[25]. The warm-up started with fifteen minutes at 75% of the maximal heart rate (HR_{max}) reached during the graded exercise test and was followed by three fast pedalling intervals (100 rpm and 90% of HR_{max}) separated by one-minute soft-pedalling rests (75% of HR_{max}). The warm-up ended with an easy three-minute rest (75% of HR_{max}). Finally, the subjects did a 5MT and were instructed to pace it to complete the entire duration. The protocol ended with a ten-minute cool down at 65% of HR_{max}. Participants performed both tests on their own bikes, set up on the Tacx Neo Smart 2T bike trainer (Tacx International, Rijksstraatweg, The

Netherlands) and had visual access to real time power, heart rate and cadence data obtained from the trainer[26]. During both tests, we analysed gas exchange (CPX / D Med Graphics, St. Paul, MN, EE. UU.), monitored heart rate with the Polar Team Pro® tool (Polar Electro, Finland) and Rate of Perceived Exertion with the RPE scale CR-10[27].

Statistical analysis

We described performance data as mean (SD), and explored associations between each variable and VO_{2max} using independent univariate general linear regressions (*Table 1*). To predict VO_{2max} we created two separate Bayesian general linear models, the first including all performance data obtained during the graded test, and the second including data from the 5MT. Then, we carried out a forward stepwise selection analysis to identify which combination of performance variables led to the best predictive equation for both scenarios.

We performed data cleaning, manipulation, and analyses in Microsoft Excel 16.43 (Microsoft Corp.) and R version 4.0.2. We performed Bayesian general linear models using the Stan computational framework (http://mc-stan.org/) accessed with *brms* package[28]. In the Bayesian models, we chose a regularized horseshoe prior for the current study due to the advantages discussed by Piironen and Vehtari[29]. Stepwise variable selection was achieved using the predictive projection technique, accessed with *projpred* package[30], and based on leave-one-out cross-validation (LOO-CV)[31]. We judged the best model size in each scenario by the mean log predictive density and the root mean square. After validating the models, we explored the residuals of the final models for normality, homogeneity, and independence assumptions. We checked the normality assumption of the residuals by means of a normal Q-Q plot of residuals. Additionally, we assessed the proportion of the variance explained using Bayesian R^2 [32]. We present Markov chain Monte Carlo and model diagnoses of all models in *Supplementary Files 2 and 4.*

Table 1. Univariate linear regression coefficients between VO_{2max} and study variables.

	Mean ± SD	**β**	**SE**	**95% CI**	**R^2**
Body weight (kg)	71.4 ± 8.6	-0.57	0.14	-0.84 to -0.29	0.29
Incremental test					
Maximal HR (bpm)	178 ± 11	0.29	0.13	0.04 to 0.54	0.12
Power Output at VO_2 max (W)	320 ± 46	0.13	0.02	0.08 to 0.17	0.41
Relative Power Output at VO_2max (W/kg)	4.5 ± 0.8	10.8	0.68	9.47 to 12.14	0.86
HR at VO_2 max (bpm)	177 ± 10	0.28	0.14	0.02 to 0.56	0.11
Relative HR at VO_2 max (% HR max)	99 ± 2	-0.43	0.62	-1.63 to 0.79	0.03
Cadence at VO_2 max (rpm)	95 ± 9	0.45	0.13	0.19 to 0.72	0.22
RPE at VO_2 max (AU)	18 ± 1	0.69	1.15	-1.47 to 2.91	0.03
Coggan test					
Five-minute power output (W)	355 ± 56	0.04	0.01	0.01 to 0.07	0.17
Five-minute power output (W/kg)	5 ± 0.9	8.87	0.87	7.21 to 10.55	0.71
Five-minute heart rate (bpm)	178 ± 10	0.12	0.14	-0.15 to 0.38	0.04
Five-minute relative heart rate (% HR max)	100 ± 5	-0.50	0.27	-1.03 to 0.02	0.09
Mean cadence (rpm)	95 ± 9	0.34	0.14	0.06 to 0.62	0.13
Five-minute RPE (AU)	20 ± 0	-0.51	2.87	-5.87 to 5.29	0.02

SD = Standard Deviation; β = mean estimated coefficient; SE = Standard Error, CI = Credibility Interval; Bpm= beats per minute; W=Watts; Rpm= revolutions per minute; AU=Arbitrary Units.

RESULTS

VO_{2max} prediction from performance data

According to the univariate models, participants with higher VO_{2max} in the graded test had lower body mass and in the same test achieved higher absolute and relative power, absolute heart rate and cadence (*Table 1*). The stepwise multiple regression analysis produced an equation for VO_{2max} with a single explanatory variable, which was the RPO at VO_{2max} during the graded test (R^2 = 0.86, 95% CI = 0.81 to 0.88). This equation was presented as $VO_{2max} = \beta_0 + \beta_1 * VO_{2max}$ RPO and its coefficients are shown in *Table 2*. A more detailed summary of results of the complete model and stepwise selection are presented in the *Supplementary File 1*.

Table 2. Regression coefficients for model 1, VO_{2max} prediction based on incremental test variables.

Coefficient	Mean	Standard Error	95% Credibility Interval
(β_0) Intercept	12,16	3,11	6.1 to 18.25
(β_1) Relative Power Output at $VO_{2\,max}$ (W/kg)	10,8	0,68	9.47 to 12.14
(σ) Standard Deviation	3,51	0,4	2.84 to 4.39

VO_{2max} prediction from a 5MT

Participants with better VO_{2max} in the graded test achieved higher absolute and relative power outputs and higher cadence in the 5MT (*Table 3*). VO_{2max} obtained during the 5MT was statistically comparable with that attained in the GXT (t(45) = -0.73; p = .47) with an almost perfect linear correlation (Adjusted R^2 = .988 , p <.0001). In line with the final model for the graded test variables, the stepwise multiple regression analysis produced an equation for VO_{2max} with a single explanatory variable, which was the average RPO during the 5MT (R^2 = 0.71, 95% CI = 0.61 to 0.77). This equation was presented as $VO_{2max} = \beta_0 + \beta_1$ x 5 min RPO and its coefficients are shown in *Table 3*. As an example, a cyclist delivering a RPO of 6 W/kg, would have an estimated VO_{2max} of 16.61 + 8.87 × 6 = 69.83 ml/min/kg. A more detailed summary of results of the complete model and stepwise selection are presented in the *Supplementary File 3*. The association between RPO at VO_{2max} and the 5MT is presented in Figure 1.

Table 3. Regression coefficients for model 2, predicting $VO_{2\,max}$ based on 5MFT variables.

Coefficient	Mean	Standard Error	95% Credibility Interval
(β_0) Intercept	16,61	4,42	8.13 to 25.21
(β_1) Five-minute Relative Power Output (W/kg)	8,87	0,87	7.21 to 10.55
(σ) Standard Deviation	4,99	0,54	4.07 to 6.2

Figure 1: Left panel, association between power outputs in the GXT and 5MT (r = 0.61); Right panel, association between observed and predicted VO_{2max}.

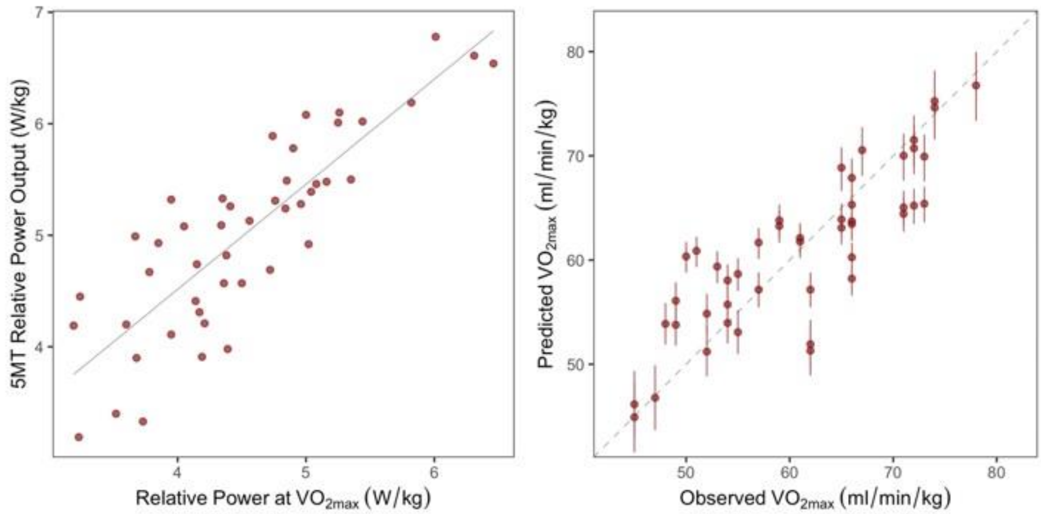

Table 4. Predicted values for VO_{2max} according to the results

RPO at min 5 (W/kg)	3	3.5	4	4.5	5	5.5	6	6.5	7
Estimated VO_{2max} (ml/min/kg)	43.2	47.8	51.9	56.5	60.9	65.5	69.8	74.4	78.7

DISCUSSION

The aim of this study was to examine the ability of a multivariate model to predict VO_{2max} using performance data from a 5MT. The main findings of the study were as follows: a) power output adjusted to body mass was the best explanatory variable for VO_{2max} and b). VO_{2max} obtained during a GXT can be predicted through a single-variable equation based on a 5MT and which is presented as $VO_{2max} = 16.61 + 8.87 \times 5$ min RPO.

To the best of our knowledge, this is the first study that has assessed whether the five-minute interval proposed in the Coggan protocol could be used for the prediction of VO_{2max} obtained through laboratory gas-exchange methods. The testing proposed by Coggan has been widely researched in the last years, though most studies have focused on the twenty-minute interval for the assessment of threshold power[17]. Previous studies have shown strong correlations between RPO during short intervals, maximal aerobic power and VO_{2max}. Novak et al. reported strong correlations between relative power output during fifteen-second to ten-minute intervals, maximal aerobic power ($r = 0.70$ – 0.94, $p < 0.001$) and VO_{2max} ($r = 0.82–0.88$, $p < 0.001$)[2]. Sanders et al. reported that an eight-minute interval could be used as a predictor of endurance performance given its relationship with several laboratory-set thresholds although its relationship with VO_{2max} in particular was not tested in this study[33]. Finally, Eston et al. showed strong correlations between two and four-minute submaximal tests and VO_{2max} obtained from graded exercise testing ($r = 0.79 - 0.92$)[34].

In line with these previous findings, RPO during the 5MT in our study was strongly correlated to the RPO at the VO_{2max} intensity ($r = 0.61$) and VO_{2max} itself ($R^2 = 0.71$, 95% CI = 0.61 to 0.77). Accordingly, we proposed a predictive formula for estimating VO_{2max} from RPO during a 5MT. One of the testing protocols that is most widely used in the coaching field was designed by Coggan and includes a 5-minute effort among the recommended intervals[25]. Further, Coggan proposed a power profile chart in which mean power output during a 5-minute effort could be used to categorize riders from novice to world class. When applying our predictive formula to the rider categorization suggested by Coggan, world class and exceptional riders would be represented by VO_{2max} values above 77,5 and 71,9 ml/kg/min, respectively[25]. These values are in line with those previously reported for elite cyclists and meet the criteria used to categorize endurance athletes according to their fitness level[19,23,35]. Given all the above, and that field testing can be done more easily as opposed to laboratory testing, we consider that our predictive formula may represent an interesting option for cyclists, coaches and scientists who do not have gas exchange measurement instruments available.

Several authors have proposed methods for predicting VO_{2max} through incremental tests based on power output[36,37]. Although these methods may deem acceptable, the protocol compliance might be affected by the practical difficulties associated to the adjustments to the power output increments that these tests establish. With regard to this, Astorino et al. showed that a self-paced cycle protocol elicited higher VO_{2max} compared to a ramp protocol[38]. Furthermore, Foster et al. compared the physiological responses between a self-paced laboratory 5 km cycle time trial and a graded exercise test using a cycle ergometer. They found that VO_{2max}, HR, ventilation, and blood lactate levels were significantly greater in the 5 km time trial compared to the graded exercise test[39]. . Contrary to the GXT, the 5MT performed in our study was self-paced[25]. The cyclists were required to produce the highest possible power output and could use their own pacing strategy. This brings us to another question: ¿Could the pacing strategy impact VO_{2peak} values obtained during the 5MT? Two previous studies have assessed VO_2 behavior during 5-minute all out efforts performed by cyclists who followed different pacing strategies[9,10]. In both cases, although mean VO_2 values observed during the 5-minute intervals were similar, faster paces during the start of the interval yielded higher VO_{2peak} values. Our study was not designed to assess the differences in pacing and this could represent an interesting opportunity for future research[40].

In contrast with previous research, which normally focused on specific fitness levels (either recreational, trained or elite), the current study included participants with a wide range of fitness levels (11 World Tour, 12 U23/Elite, 12 Master and 11 recreational cyclists)[17]. Additionally, compared to preceding investigations, this study's sample size was also larger. Consequently, the equation obtained in this study is generic and not specific to fitness levels. On the one hand, this strengthens the practical application of our findings since it could be used at many performance levels. In the authors' opinion, an equation that can be used among broad cycling populations could be very interesting for coaches, who typically work with athletes of different fitness levels. On the other hand, however, slight differences in the coefficients could exist if we had estimated independent equations for each fitness level. In this regard, the diagnostic plot provided in the right panel of Figure 1 suggests that the prediction error at the two extremes of the observed VO_{2max} range was small and comparable between the participants with the highest and lowest fitness levels. However, as inherent in linear modeling, prediction uncertainty is still lower at the center and higher at the extremes. For this reason, it might be interesting to complement the present results in future research by addressing the possible differences in the coefficients and/or prediction accuracy when fitting separate, level-specific equations instead of the generic one developed in this study.

Several aspects should be taken into account when attempting to extrapolate our results to the field: modern power meters are generally precise but may vary in their trueness[41]. Therefore, the extrapolation of our predictive formulas to tests performed with other measuring systems must be exercised with caution. Further, power variability, pedalling characteristics, cadence and biomechanics are different in the field compared to the laboratory setting[42,43]. The protocol used in the current study was characterized by several limitations. Firstly, we obtained VO_{2max} values from a GXT based on previous research and characterized by 3-minute steps. It is well known that GXT protocol design may influence VO_{2max} testing results and the evidence regarding the suitability of this duration for the assessment of VO_{2max} is contradictory: while some studies show equal VO_{2max} values obtained with 1,2 and 3-minute steps, others have reported that shorter tests provide higher values and vice-versa[3–5,44–48]. Secondly, several authors have suggested that the inclusion of verification bouts after a GXT could help confirm whether true VO_{2max} was attained during the test[5,49]. This procedure has, however, several limitations such as lack of standardization, homogeneity and scarcity of previous research with study samples such as ours[50,51]. In this study VO_{2max} obtained during the 5MT was statistically comparable with that attained in the GXT ($t(45) = -0.73$; $p = .47$) with an almost perfect linear correlation (Adjusted $R^2 = .988$, $p <.0001$). Finally, the implementation of our 5MT requires taking into consideration that time to exhaustion at VO_{2max} intensity varies among cyclists of the same apparent level and that VO_2 kinetics vary among individuals [12,52]. Also, as it is commonly reported in the literature, a VO_2 plateau was not seen in all cases during the GXT[6]. Secondary measures such as rating of perceived exertion, respiratory exchange ratio, heart rate and voluntary fatigue were used as criteria for test termination in these cases. Although our GXT were performed until voluntary fatigue when a VO_{2max} plateau was not observed, which minimizes the risk of early termination and VO_{2max} underestimation, some authors have suggested that secondary termination criteria may affect VO_{2max} calculations during GXT[4].

PRACTICAL APPLICATIONS

By using a simple 5MT implemented into a field training session, coaches, and cyclists with a wide range of performance levels can assess VO_{2max} through a single variable predictive equation. This assessment may contribute to more accurate and individualized training programs and may also reduce the need to access to a laboratory setting to evaluate this cardiorespiratory parameter.

CONCLUSIONS

In this study, in a sample of forty-six cyclists with a wide range of fitness levels, VO_{2max} obtained through gas exchange testing during a GXT could be predicted by a single-variable formula based on relative power output obtained during a 5MT.

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4. Relación entre UPF, umbral ventilatorio y PCR en ciclistas de carretera

Relationship between functional threshold power, ventilatory threshold and respiratory compensation point in road cycling

BACKGROUND

The purpose of this study was to assess the relationship between power output and relative power output at the functional threshold power, ventilatory threshold and respiratory compensation point in road cyclists.

METHODS

Forty-six road cyclists (age 38 ± 9 years; height 177 ± 9 cm; body mass 71.4 ± 8.6 kg; body mass index 22.7 ± 2.2 $kg\cdot m^{-1}$; fat mass 7.8 ± 4%, VO_{2max} 61.1 ± 9.1 $ml\cdot min^{-1}\cdot kg^{-1}$) performed a graded exercise test in which power output and relative power output at the ventilatory landmarks were identified. Functional threshold power was established as 95% of the power output during a 20-minute test.

RESULTS

Power output and relative power output at the functional threshold power were higher than at the ventilatory threshold ($p < 0.001$). There were very large to near perfect correlations for power output (95% CI for r from 0.71 to 0.9) and relative power output (95% CI for r from 0.79 to 0.93) at the functional threshold power and respiratory compensation point. Mean bias in power ouput and relative power output measured at RCP compared with FTP was not significant (mean bias 95% CI from -7 to 10 W and -0.1 to 0.1 W/kg, respectively).

CONCLUSIONS

Power output and relative power output at the functional threshold power are higher than at the ventilatory threshold. Power output and relative power output at the functional threshold power and respiratory compensation point are strongly related, but caution is required when using both concepts indistinctly.

Keywords: *endurance; power output; power meter; training; performance*

Introduction

Road cycling is an endurance sport in which performance is characterized by extreme aerobic requirements[1]. These fitness values can be measured as maximal, such as maximal oxygen consumption (VO_{2max}), or submaximal parameters[1]. The contemporary gold standard approach for assignment of exercise intensity involves normalization based on percentages of maximal heart rate or VO_{2max}, as identified through cardiopulmonary incremental exercise testing. However, exercise prescription that relies on percentages of maximal parameters is based on several debatable topics: First, it assumes that exercise intensity exists upon a continuum and second, that the metabolic responses to a specific percentage of the maximum are identical among individuals[2]. In reality, VO_2 kinetics vary when submaximal landmarks such as the lactate threshold, critical power and maximal lactate steady state are reached[3]. These thresholds are currently used to determine exercise intensity domains and may occur at varying VO_2 percentages across individuals[4]. Therefore, selection of exercise based on a fixed percentage of VO_2 for all individuals may result in inadequate exercise prescription. The importance of these physiological landmarks has been highlighted in recent research, which has shown that training prescription based on threshold rather than standardized values yields greater cardiorespiratory fitness responses[5].

The ventilatory threshold (VT) and respiratory compensation point (RCP) are boundaries related to endurance performance[6]. Specifically, these two physiological landmarks are manifestations of metabolic events where homeostasis is disrupted: VT is the intensity at which ventilation and carbon dioxide production increase in parallel. On the other hand, RCP represents a work intensity at which hyperventilation occurs to buffer acidosis[7]. Thus, RCP represents the highest metabolic rate at which the system is able to maintain an elevated but steady metabolic acidosis[8]. Further, when correctly assessed, RCP is capable of accurately predicting the power output associated with maximal metabolic steady state[9]. Exercise above these thresholds results in accumulation of fatigue-inducing metabolites, rapid increases in intramuscular and arterial lactate, hydrogen concentration and changes in motor unit recruitment[6]. As training programs aimed at each of these thresholds will produce specific and different central and peripheral adaptations, the ability to precisely determine the VT and RCP in endurance sports remains crucial[5,10]. Gas exchange measurements during graded exercise tests (GXT) are normally used to assess VT and RCP in endurance sports in general and road cycling in particular[11,12].

Although these laboratory determinations allow direct measurements, they also present several setbacks such as the dependence on educated staff, laboratory equipment and a specific location for the assessment. Given these disadvantages, the interest in flexible, less expensive and simple indirect field measurements that would allow ventilatory determinations has risen in the last years[13].

Studies that compare laboratory with field measurements often use time to complete a certain distance or average speed as performance measures. However, external conditions like wind, road surface, gradient, rider mass and size have a large influence on these performance variables[13]. Power output (PO) is independent of those external influences and therefore is more appropriate to use as a valid parameter in field testing conditions. As an answer to this specific need, mobile power meters represent the possibility of assessing PO in the field with reduced associated costs[13]. Given their availability and user-friendly nature, it could be suggested that the use of mobile power meters may represent an alternative to laboratory assessments for the determination of ventilatory landmarks[14].

One of the most researched field alternatives for the assessment of steady-state parameters is the Functional Threshold Power (FTP) concept, which was first used by Coggan and Allen and was defined as the highest possible PO that could be sustained in a quasi-steady state[15]. According to Coggan and Allen, FTP can be predicted by subtracting 5% to the mean PO obtained during a 20-minute maximal effort that is included in their specific testing protocol[15]. The physiological basis of this threshold has been previously suggested in several studies: it has been verified that FTP can be sustained over long time periods (50-60 minutes), with high correlations reported for FTP and key physiological steady state landmarks such as maximal lactate steady state[16,17]. Further, the relationship between ventilatory landmarks and FTP obtained from a 20-minute test has been studied twice, with stronger correlations reported for RCP than for VT[18,19]. It should be highlighted, however, that these studies were characterized by small sample sizes (n = 15 in both cases) and heterogenous methodologies. Further, previous research has suggested that, despite the high correlations reported for FTP and steady state markers, these concepts should not be used interchangeably due to the large limits of agreement commonly observed between them[20,21].

Given all the above, despite its importance for the practical field, the relationship between PO and relative power output (RPO) measured at VT, RCP and FTP estimated from a 20-minute test remains scarcely researched. Consequently, the objective of the current study was to assess the relationship between PO and RPO at VT, RCP and FTP estimated from a 20-minute test in a large sample of road cyclists characterized by a broad range of cardiorespiratory fitness levels.

Materials and methods

Participants

Forty-six road cyclists were recruited for the study (age 38 ± 9 years; height 177 ± 9 cm; body mass 71.4 ± 8.6 kg; body mass index 22.69 ± 2.2 kg/m^2; fat mass 11.1 ± 4.5%; VO_{2max} 61.1 ± 9.1 ml·min^{-1}·kg^{-1}). The inclusion criteria were a) current owner of a cycling license: World Tour, Elite/U23, Masters or recreational; b) absence of surgical procedures and injuries in the six months prior to the study c) absence of drug use in the six months prior to the study. After being informed of the benefits and potential risks of the investigation, each participant completed a health-screening questionnaire and provided written informed consent prior to participation in the study. The study followed the ethical guidelines of the 2013 Declaration of Helsinki and received approval from the Research Ethics Committee of the autonomous region of Aragon, Spain (PI19/447).

Experimental design

Participants completed the study on two separate days with a 72-h rest in between. Data were collected under similar environmental conditions (17-18 ºC, 45–55% relative humidity) between 10:00 am and 12:00 am. On the first day, the body composition of all cyclists was assessed through the electrical impedance method (BC-602, Tanita Co., Tokyo, Japan). Height was measured with a SECA 214 stadiometer (Seca., Hamburg, Germany), which is graduated up to 1 mm. After the body composition assessment, participants performed a GXT with gas exchange analysis (CPX / D Med Graphics, St. Paul, MN, EE. UU.) based on previous protocols[22]. The GXT commenced at a workload of 150 W, with 25 W increments every three minutes until exhaustion. In all cases, a five-minute warm-up at 100 W was allowed before the commencement of the test. PO and RPO were measured at two common ventilatory landmarks: VT was determined using the criteria of an increase of the ventilatory equivalent of O_2 (VE / VO_2) without a concomitant increase of the ventilatory equivalent of CO_2 (VE / VCO_2), the first loss of linearity in pulmonary ventilation (VE) and the loss of linearity of carbon dioxide ventilation (VCO_2)[11]. RCP was determined using the VE versus VCO_2 relationship described by Wasserman and Beaver (1986). RCP was defined as the VO_2 value corresponding to the point of departure from linearity of the VE versus VCO_2 relationship[11]. Power output values from the incremental test were plotted against VO_2 values, and the regression equation derived was used to determine the power output at the RCP and VT. The current protocol and the methods of VT and RCP detection have been used in several studies with professional cyclists and have been shown to be valid and reliable[23–27]. The assessment ended 1) after a plateau of the VO_2 curve was reached or 2) at voluntary fatigue when two of the three secondary criteria were reached: 100% of estimated HR_{max}; Rate of Perceived Exertion (RPE) of ≥18 and respiratory exchange ratio of ≥1.15[28]. Participants performed the GXT tests on their own bike, set up on the Tacx Neo Smart 2T bike trainer (Tacx International, Rijksstraatweg, The Netherlands). The Power Tap P1 pedals (PP1, CycleOps, Madisson, USA) were used for the assessment of power and cadence[29].

On the second assessment, the participants performed the testing protocol suggested by Coggan and Allen[15], again in the laboratory setting. They could view their progress on a computer monitor and were provided with information on the time completed and gear selected; all other information was blinded; verbal encouragement was not provided and water was allowed ad libitum. The warm-up duration was 50 min as follows: a) 20 min at a self-selected easy intensity; b) 3 × 1-minute fast pedalling accelerations (100–105 rpm) with a 1-minute recovery between efforts; c) 5 minutes at a self-selected easy intensity; d) 5-minute time-trial; e) 10-minutes at a self-selected easy intensity; and a 5-minute rest. The main part of the test consisted of a 20-minute maximal effort, where the participants had to produce the highest mean power output possible for this duration and adopt their personal pacing strategies. FTP was determined as 95% of the mean power output of the 20-minute effort.

Statistical analysis

Data cleaning, manipulation and analyses were performed with R version 4.0.2, the *easystats* ecosystem and the *rstatix* package[30,31]. Data were visually inspected, and normality assumption was assessed using the Shapiro-Wilk test. Accordingly, data were described as mean ± standard deviation or median [interquartile range], as appropriate. Performance data were grouped by metric, PO and RPO. Then, main differences in each metric among thresholds: FTP, VT and RCP were assessed using one-way repeated measures ANOVA (*F*) when data met normality assumption or Kruskal-Wallis test (*H*) otherwise. Effect size for the main differences was calculated using η^2_G or η^2_H for the *F* or *H* statistics, respectively, which can be interpreted as small < 0.06, moderate 0.06-0.14, and large > 0.14[32]. When main differences were statistically significant, post-hoc multiple pairwise comparisons were made using *t*-test for repeated measures or Dunn's test, as appropriate. Bonferroni corrections were applied in all pairwise comparisons, and statistical significance was assumed when $p < 0.05$. Subsequently, correlations were calculated to determine the associations between each metric at FTP and at its related ventilatory thresholds. Pearson's r was used when all variables satisfied the normality assumption, otherwise Spearman's ρ was elected. All correlation coefficients were expressed as the mean estimate (95% confidence interval), and the magnitude of correlation coefficients was interpreted as small = 0–0.3, moderate = 0.31–0.49, large = 0.50–0.69, very large = 0.70–0.89, and near perfect = 0.90–1.00[33]. Additionally, Bland-Altman plots and 95% limits of agreement (LoA) were used to represent and compare PO and RPO at FTP with the same metric metrics at VT and RCP. The 95% LoA were calculated as the mean difference ± 1.95 SD of the differences. The mean difference (bias) between variables was calculated with the corresponding 95% confidence intervals.

Results

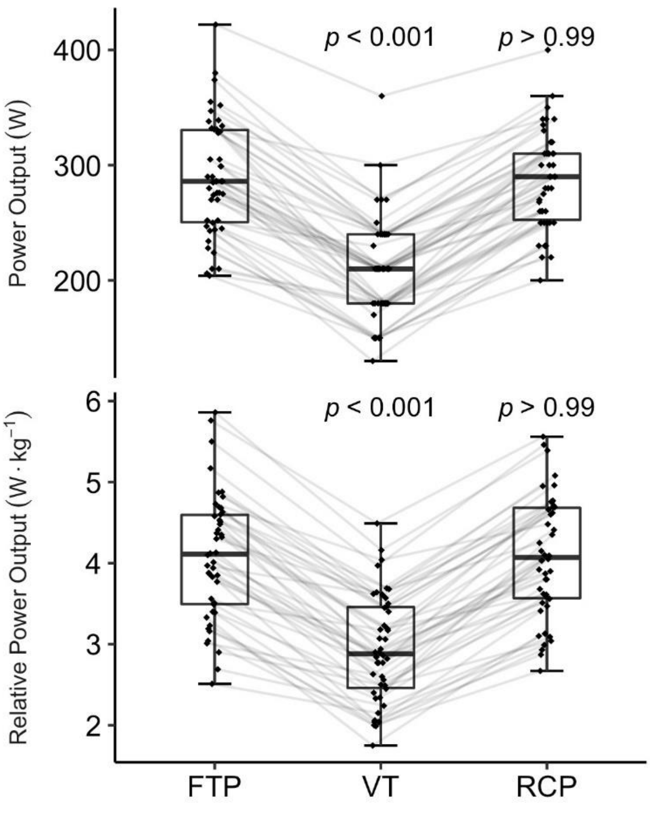
Power Output at each ventilatory landmark can be found in Table I. Large main differences in PO were found between thresholds ($H(2) = 85.5$, $p < 0.001$, $\eta^2_H = 0.42$). Specifically, post-hoc pairwise comparisons showed that PO at FTP was higher than at VT ($p < 0.001$). Similarly, there were large main differences in RPO between thresholds ($F(2, 90) = 263$, $p < 0.001$, $\eta^2_G = 0.36$). Post-hoc pairwise comparisons showed that RPO at FTP was higher than at VT ($p < 0.001$). Individual datapoints are shown in Figure 1.

Table I: Absolute and relative power output in each ventilatory landmark.

	FTP	VT	RCP
PO (W)	288.7 ± 50	210 [180-240]$_{<FTP}$	286.9 ± 42.2
RPO (W/kg)	4.1 ± 0.8	2.9 ± 0.7$_{<FTP}$	4.1 ± 0.7

Data are expressed as mean ± standard deviation except PO at VT, that has been expressed as median [interquartile range]. Subscripts indicate statistically significant differences between thresholds and their direction. PO = Power Output; RPO = Relative Power Output; Ventilatory landmarks: VT = Ventilatory Threshold; RCP = Respiratory Compensation Point.

Figure 1: Comparison of PO and RPO at FTP, VT and RCP.



Correlational analysis showed large to almost-perfect correlations between metrics at FTP and at the ventilatory thresholds (Table II). In spite of these correlations, Bland-Altman analysis revealed that both, PO and RPO, were systematically higher when measured at FTP compared with VT (Mean bias 95% CI from 71 to 90 W and 1.02 to 1.27 W/kg, respectively). By contrast, mean bias in PO and RPO measured at RCP compared with

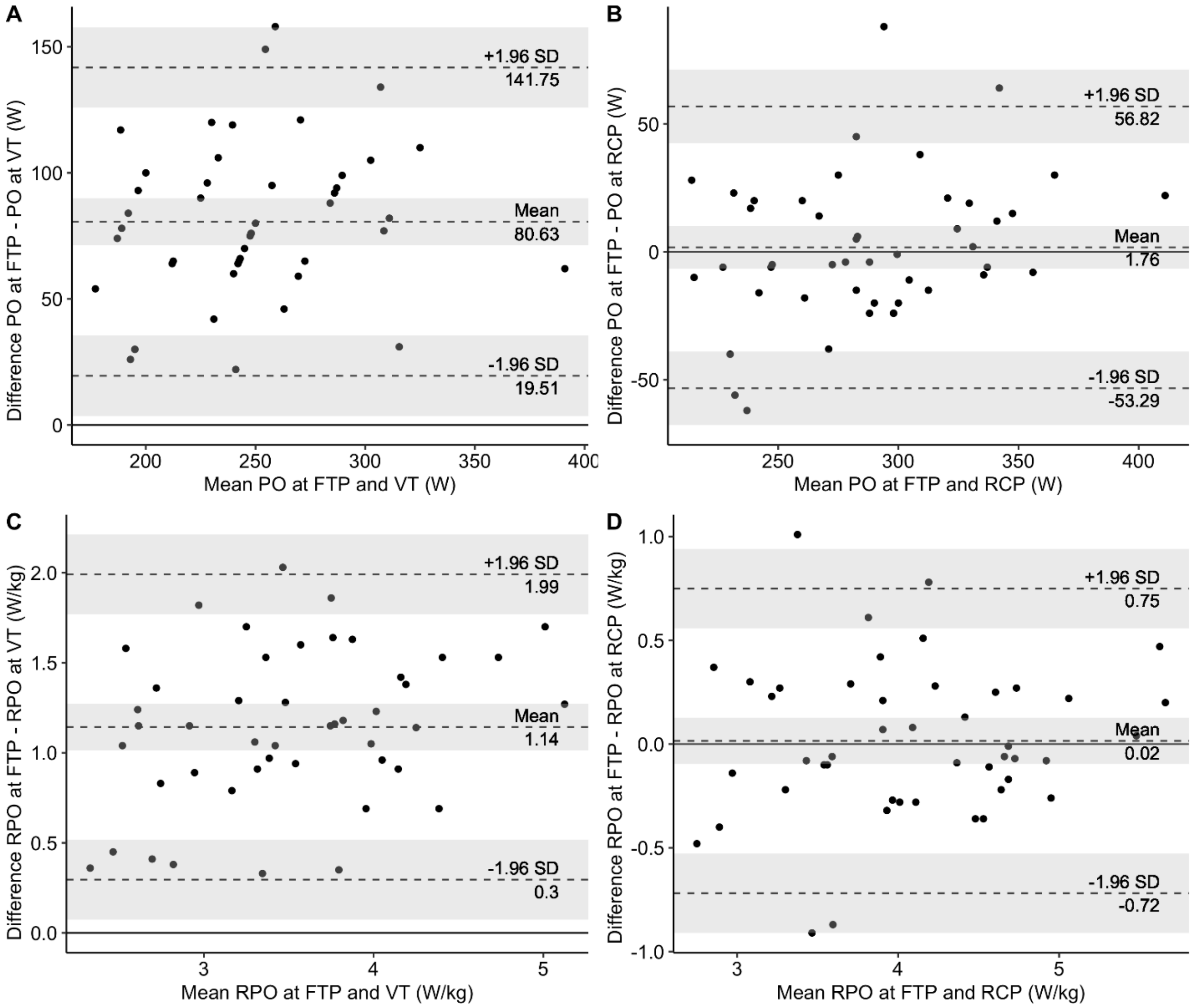
FTP was not significant (Man bias 95% CI from -7 to 10 W and -0.1 to 0.1 W/kg, respectively) (see Figure 2).

Table II: Correlation coefficients between each metric at FTP and its correspondent value at each ventilatory landmark.

	PO (W)		RPO (W/kg)	
	Estimate	95%CI	Estimate	95%CI
VT	$\rho = 0.77$	0.61 to 0.87	$r = 0.83$	0.71 to 0.9
RCP	$r = 0.83$	0.71 to 0.9	$r = 0.88$	0.79 to 0.93

PO = Power Output; RPO = Relative Power Output; Ventilatory landmarks: VT = Ventilatory Threshold; RCP = Respiratory Compensation Point

Figure 2: Mean bias between ventilatory landmarks PO and RPO.



A = PO at FTP vs VT; B = PO at FTP vs RCP; C = RPO at FTP vs VT; D =RPO at FTP vs RCP. Limits of agreement and mean bias are indicated with dotted lines, whereas grey-shaded areas represent the 95% CI for each value.

Discussion

In this study, the relationship between FTP, VT and RCP was assessed in a sample of road cyclists with a wide range of cardiorespiratory fitness levels. The main findings were as follows: a) there were significant differences in both PO and RPO measured at FTP compared to VT but not RCP; b) there were large to near perfect correlations between PO and RPO measured at FTP and the same variables obtained at RCP.

Training prescription based on threshold rather than standardized values yields greater cardiorespiratory fitness responses and is the preferred training prescription option according to previous research[2,5]. Physiological landmarks such as VT and RCP are commonly used in the practical field to separate exercise intensity domains and for training prescription. In the current study, we found significant differences measured at FTP compared to VT. More specifically, both PO and RPO, were systematically higher when measured at FTP than at VT (Mean bias 95% CI from 71 to 90 W and 1.02 to 1.27 W/kg, respectively). By contrast, mean bias in PO and RPO measured at RCP compared with FTP was not significant (Mean bias 95% CI from -7 to 10 W and -0.1 to 0.1 W/kg, respectively). The metabolic rate associated with the RCP intensity sets the boundary between heavy and severe exercise intensity domains and is therefore critical for training prescription[34,35]. Our findings match those obtained in previous research that reported very large (r = 0.80) correlations between FTP and RCP[18,19]. A close relationship between both markers was to be expected, as both concepts relate in theory to exercise intensities in the domains of the maximal metabolic steady state. Previous studies have shown that the time to exhaustion at the FTP intensity closely matches that of the maximal lactate steady state, and the PO at both intensities is closely related (Mean bias ± 95% LoA of 1.4% ± 9.2%) with nearly perfect correlations between both markers (r = .91)[17,20]. However, other studies have reported larger differences between both concepts and some authors have advised against using them interchangeably[21].

The differences in the relationships reported for the RCP and FTP across different studies could be explained by the variable methodologies used to determine both physiological landmarks: different warm-up protocols have been used before the 20-minute test in several studies. The intervals proposed in these protocols generate different levels of fatigue which can result in varying PO during the 20-minute test[18,19]. More importantly, the determination of PO at the ventilatory thresholds through GXT is associated to an important limitation: during GXT, none of the physiological parameters reach a steady state because of the continuously changing metabolic demands. This results in that measured VO_2 will not reflect the true metabolic needs for any given PO. As a result, every PO imposed during constant exercise will elicit a higher VO_2 than measured at the same PO during ramp exercise[3,36]. Although the dissociation between constant intensity exercise $\dot{V}O_2$ and ramp $\dot{V}O_2$ at a given work rate might be mitigated in slowly-increasing ramp protocols such as the one used in the current study, overestimating PO at a given metabolic rate with this kind of approach remains a possibility and must be taken into account[37]. Several authors have recently suggested approaches to fix this issue through mean response time corrections for moderate intensities and translation strategies for heavy exercise[36,37]. However, these new proposals may be difficult to implement in the practical setting, where submaximal and maximal ventilatory testing is performed simultaneously with lactate measures, often with limited time availability. Further, these translation strategies have not been tested in elite cyclists, whose VO_2 behavior during a GXT may be different to that of a non-athlete[38–40].

A recent meta-analysis pooled studies that had previously compared PO at the critical power, maximal lactate steady state and RCP among other physiological landmarks[41]. The authors concluded that the metabolic rates at these landmarks cannot be synonymous with the maximal metabolic steady state. However, studies have consistently shown that the critical power corresponds to an exercise intensity located in the severe intensity domain and can usually be held for limited time periods[42,43]. Accordingly, critical power should not be considered as the gold standard for the assessment of the maximal metabolic steady state. Some authors have shown that when $\dot{V}O_2$ kinetics is appropriately accounted for, the power output that elicits the $\dot{V}O_2$ at RCP conforms very closely to the maximal metabolic steady state[44]. In the current study, PO at RCP and FTP were very closely related. This result is coherent with the fact that the metabolic rate at the FTP has been shown to be lower that at the critical power and can therefore represent a closer approximation to the maximal metabolic steady state[45,46]. However, as previously explained, the determination method of PO at RCP in this and other earlier studies has important setbacks that question the accuracy of this determination.

The major strength of the current study is the relatively large sample size when compared to previous similar studies[14]. Furthermore, instead of focusing on a specific performance level, the relationship between these landmarks was verified in a sample composed by participants of different fitness levels (from recreational to World Tour cyclists). Although PO at the RCP and FTP were closely related in this sample and it could be tempting to use both parameters interchangeably, caution is required as the methodology used in our study for the assessment of PO at the RCP is associated to important setbacks.

Conclusions

In a sample of forty-six road cyclists characterized by a broad range of fitness levels, significant differences were found in both PO and RPO measured at FTP compared to VT. However, differences in PO and RPO were not significant between FTP and RCP. Further, there were large to near perfect correlations between PO and RPO measured at FTP and the same variables obtained at RCP. Although the mean bias in PO and RPO measured at RCP compared with FTP was not significant, caution is required when attempting to use both physiological landmarks interchangeably, given that the determination method of PO at the RCP in the current study could have overestimated PO at this metabolic rate.

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5. UPF como alternativa a los umbrales de lactato en ciclismo de carretera

Functional threshold power as an alternative to lactate thresholds in road cycling

ABSTRACT

This study assessed the relationship between Functional Threshold Power (FTP) and seven lactate landmarks (D_{max}, modified D_{max}, fixed blood lactate concentrations of 2 and 4 mmol·L^{-1}, lactate increases of 1 and 2 mmol·L^{-1} above baseline and lactate increases of 1.5 mmol·L-1 above the point of minimum ratio between lactate and work rate) in a sample of forty-six road cyclists with a wide range of fitness levels (age 38 ± 9 years; height 177 ± 9 cm; body mass 71.4 ± 8.6 kg; body mass index 22.7 ± 2.2 kg·m^{-1}; fat mass 7.8 ± 4%, VO_{2max} = 61.1 ± 9.1 ml·min^{-1}·kg^{-1}). The cyclists performed a graded exercise test in which power outputs (PO) at the lactate landmarks were identified. FTP was established as 95% of the PO during a 20-minute test. Significance was set as ($p < 0.05$). Statistical analyses revealed large to very large correlations between PO, relative power output (RPO) and cadence at FTP and lactate thresholds established through D_{max}, modified D_{max} and fixed lactate concentrations of 4 mmol·L^{-1} (r = 0.68 – 0.93). Significant differences ($p < 0.001$) were also observed for PO and RPO at FTP, fixed blood lactate concentrations of 2 mmol·L^{-1} and lactate increases of 1 mmol·L^{-1} above baseline. Therefore, though FTP estimated from a 20-minute test is strongly related to several lactate landmarks, caution is required when substituting this concept for lactate thresholds. This information will allow coaches, cyclists and scientists to better choose assessments when attempting to estimate lactate threshold through power-based field testing.

Keywords: Endurance, performance, training.

INTRODUCTION

The lactate threshold (LT) remains a widely recognized concept in exercise physiology and represents a key performance parameter in endurance sports such as road cycling. It marks the limit between heavy and severe exercise intensity domains and defines the intensity above which efforts can no longer be sustained in a steady state (18). Lactate measurements during graded exercise tests (GXT) are normally used to assess the LT in cyclists. Although these determinations allow direct measurements, they also present several setbacks such as the dependence on educated staff, laboratory equipment and a specific location for the assessment. Given these disadvantages, interest in flexible, less expensive and simple indirect measurements that would allow LT determinations has risen in the last years (19).

Previous research has shown relationships between lactate levels and power output (PO) during a GXT in road cyclists (15, 21). Furthermore, LTs are normally determined by assessing lactate responses to PO requirements (2). Among the laboratory-based methods for the assessment of LT, as many as 25 different procedures have been suggested, without a clear consensus among authors. Some of them use fixed lactate concentrations while others detect the first lactate rise above baseline levels. Other threshold concepts aim at detecting either lactate stable states or rapid changes in the blood lactate curve slope (7).

During the last decade, the possibility of assessing PO in the field has been provided by the exponential rise in the use of power meters among professional and amateur cyclists. These user-friendly tools allow the collection of real-time power data in the field with reduced associated costs (17). Given their availability, reduced costs, and user-friendly nature, the use of mobile power meters could represent an alternative to laboratory assessments for the determination of the LT. One of these field alternatives is the Functional Threshold Power (FTP) concept, which was first used by Coggan and Allen and was defined as the highest possible PO that could be sustained in a quasi-steady state (1). According to these authors, FTP can be predicted by subtracting 5% from the mean PO obtained during a 20-minute maximal effort that is included in their specific testing protocol (1). To date, this test has been the most researched method for FTP determination and has been compared to several LTs (21). Although correlations between FTP and several LTs have been found, many authors recommend caution when attempting to use power and lactate-based thresholds indistinctly as the magnitude of the correlations differs among individuals (21). According to the current available evidence, whether LTs and FTP can be used interchangeably remains a debatable question.

Given that previous research on the topic was limited by several elements such as small sample sizes and the utilization of few lactate landmarks, the objective of the current study was to assess the relationship between FTP and seven different lactate landmarks in a sample of road cyclists characterized by a wide range of fitness levels.

METHODS

Experimental approach to the problem

This study compared the field-based 20-minute test proposed by Coggan and Allen with physiological measures obtained using a laboratory incremental cycling test. Firstly, an evaluation was made of how FTP estimated by the 20-minute test compares to commonly used LTs assessed in a laboratory setting to determine if field and laboratory-based thresholds can be used interchangeably. Secondly, the relationship between PO during the 20-minute test and predictors of endurance cycling performance obtained with the laboratory test (PO at fixed blood lactate concentrations of 2 and 4 mmol·L^{-1}, D_{max}, modified D_{max}, lactate increases of 1 and 2 mmol·L^{-1} above baseline and lactate increases of 1.5 mmol·L^{-1} above the point of minimum ratio between lactate and work rate) was evaluated.

Subjects

Forty-six male road cyclists were recruited for the study (age 38 ± 9 years; height 177 ± 9 cm; body mass 71.4 ± 8.6 kg; body mass index 22.7 ± 2.2 kg·m^{-1}; fat mass 7.8 ± 4%, VO_{2max} = 61.1 ± 9.1 ml·min^{-1}·kg^{-1}). The inclusion criteria were a) current owner of a cycling license: World Tour, Elite/U23, Masters or recreational; b) absence of surgical procedures and injuries in the six months prior to the study c) absence of drug use in the six months prior to the study. After being informed of the benefits and potential risks of the investigation, each participant completed a health-screening questionnaire and provided written informed consent prior to participation in the study. The study followed the ethical guidelines of the 2013 Declaration of Helsinki and received approval from the Research Ethics Committee of the autonomous region of Aragon, Spain (PI19/447).

Procedures

Participants completed the study on two separate days with a 72h rest in between. Data were collected under similar environmental conditions (17-18 ºC, 45–55% relative humidity). All participants performed both tests during the same morning hours (between 10:00 a.m. and 12:00 am) in order to control for diurnal hormonal variations. The testing was performed as follows: day 1: anthropometric evaluation and GXT; day 2: Coggan's testing protocol.

Anthropometric evaluation

The body composition of all cyclists was assessed through the electrical impedance method (BC-602, Tanita Co., Tokyo, Japan) in the morning hours. Height was measured with a SECA 214 stadiometer (Seca., Hamburg, Germany), which is graduated up to 1 mm.

Graded exercise test

Participants performed an incremental exercise test with gas exchange analysis (CPX / D Med Graphics, St. Paul, MN, EE. UU.) in the laboratory. Cyclists completed the GXT test on their own bikes set up on the Tacx Neo Smart 2T bike trainer (Tacx International, Rijksstraatweg, The Netherlands) which allows power and cadence measurements. The incremental test started at 100 W and increased with 25 W every 3 minutes until a plateau of the VO_2 curve was reached or, when not seen, at voluntary fatigue when 100% of estimated HR_{max}, a Rate of Perceived Exertion (RPE) of ≥18 and respiratory exchange ratio of ≥1.15 were attained (2,15,25). Lactate measures were assessed with the Lactate Pro 2 analyzer (Laktate, Busimedic S.L, San Sebastián, Spain) and were collected from the ear lobe at the end of each 3-minute step. Baseline lactate levels were obtained at rest, one minute before the start of the GXT. PO, Relative Power Output (RPO), and cadence were measured at five common lactate landmarks: D_{max} (LT1) (5), modified D_{max} (LT2) (6), fixed blood lactate concentrations of 2 (LT3) and 4 $mmol·L^{-1}$ (LT4), lactate increases of 1 (LT5) and 2 $mmol·L^{-1}$ (LT6) above baseline (12,20) and lactate increases of 1.5 $mmol·L^{-1}$ above the point of minimum ratio between lactate and work rate (LT7) (4). A publicly available spreadsheet was used to calculate power output at the different lactate landmarks (16).

20-minute test

For the second assessment, participants performed the testing protocol suggested by Coggan and Allen (1). They could view their progress on a computer monitor and were provided with information regarding time to completion and gear choice. All other information was blinded, no verbal encouragement was provided, and water was allowed ad libitum. The warm-up duration was 50 min as follows: a) 20 min at a self-selected easy intensity; b) 3- × 1-minute fast pedaling accelerations (100–105 rpm) with a 1- minute recovery between efforts; c) 5 minutes at a self-selected easy intensity; d) 5-minute time-trial; e) 10-minutes at a self-selected easy intensity; and 5 minutes of resting. The main part of the test consisted of a 20-minute maximal effort, where participants were asked to produce the highest mean power output possible for this duration and adopt their personal pacing strategies. FTP was determined as 95% of the mean power output of the 20-minute effort.

Statistical analyses

Data cleaning, manipulation and analyses were performed with R version 4.0.2, the *easystats* ecosystem (13) and the *rstatix* packages (11). Data were visually inspected, and normality assumption was assessed using Shapiro-Wilks test. Accordingly, data were described as mean (standard deviation) or median [interquartile range] as appropriate. Performance data were grouped by metric, PO, RPO and Cadence, and main differences in each metric among FTP and lactate landmarks were assessed using the Kruskal-Wallis test (H). Effect size was calculated using η^2_H, which can be interpreted as small < 0.06, moderate 0.06-0.14, and large > 0.14 (22). When main differences were statistically significant, post-hoc multiple pairwise comparisons were made using Dunn's test. Bonferroni corrections were applied in all pairwise comparisons and statistical significance was assumed when $p < 0.05$. Subsequently, correlations were calculated to determine the associations between each metric at FTP and at its related lactate landmark (LT1-7). When all variables satisfied the normality assumption Pearson's r was used, otherwise Spearman's ρ was elected. All correlation coefficients were expressed as the mean estimate (95% confidence interval), and the magnitude of correlation coefficients was interpreted as small = 0–0.3, moderate = 0.31–0.49, large = 0.50–0.69, very large = 0.70–0.89, and near perfect = 0.90–1.00 (9).

RESULTS

There were moderate main differences in PO among landmarks (H (7) = 56.9, $p < 0.001$, $\eta^2_H = 0.14$). Specifically, post-hoc pairwise comparisons showed that PO at FTP (median 286 [interquartile range 250-330] W) was higher than at LT3 (230 [210-248] W; $p < 0.001$), and LT5 (235 [202-258] W; $p < 0.001$). Similarly, there were moderate main differences in RPO among landmarks (H (7) = 49.9, $p < 0.001$, $\eta^2_H = 0.12$). Also, post-hoc pairwise comparisons showed that RPO at FTP, median 4.1 [interquartile range 3.5-4.6] W·kg^{-1}) was higher than at LT3 (3.3 [2.8-3.7] W·kg^{-1}; $p < 0.001$), and LT5 (3.2 [3-3.6] W·kg^{-1}; $p < 0.001$). By contrast, there were small main differences in cadence among landmarks (H (7) = 15, $p = 0.04$, $\eta^2_H = 0.02$). However, post-hoc analysis showed no significant differences in any pairwise comparison involving cadence at FTP. Individual datapoints for all four variables as well as further pairwise comparison significances among thresholds are shown in Figure 1. Correlational analysis showed large to very large correlations between PO, RPO and cadence at FTP and at D_{max} or modified D_{max}. A complete detail of correlation coefficients is provided in Table 1.

Figure 1. Differences in PO, RPO and cadence among landmarks.

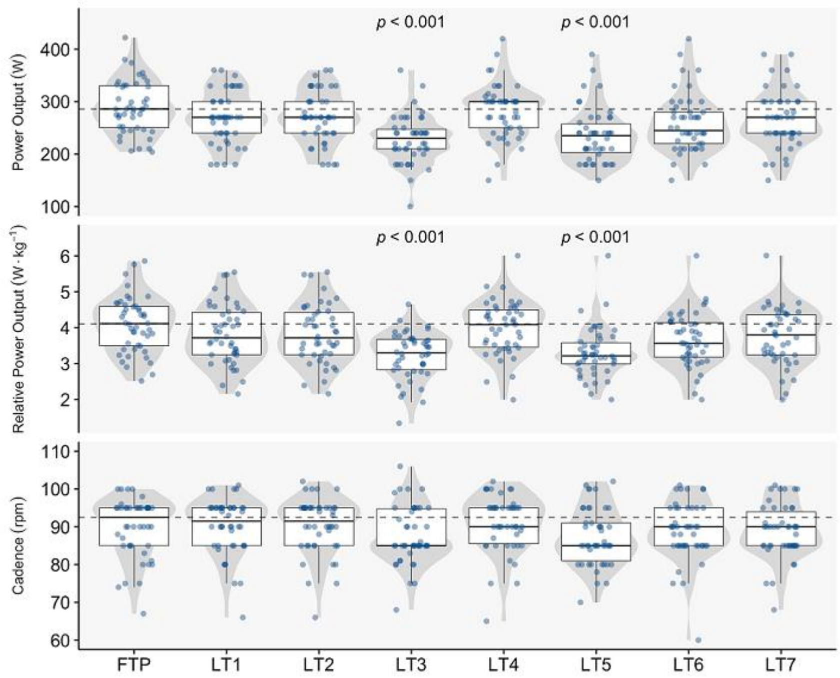

Table 1: Correlation coefficients between each metric at FTP and its correspondent value at each lactate landmark.

	PO (W)		RPO ($W \cdot kg^{-1}$)		Cadence (rpm)	
	Estimate	95%CI	Estimate	95%CI	Estimate	95%CI
LT1	r = 0.86	0.75 to 0.92	r = 0.9	0.83 to 0.94	ρ = 0.81	0.68 to 0.89
LT2	r = 0.85	0.75 to 0.92	r = 0.9	0.82 to 0.94	ρ = 0.81	0.68 to 0.89
LT3	r = 0.7	0.52 to 0.83	r = 0.74	0.58 to 0.85	ρ = 0.61	0.38 to 0.77
LT4	r = 0.81	0.68 to 0.89	r = 0.85	0.74 to 0.91	ρ = 0.88	0.78 to 0.93
LT5	ρ = 0.63	0.41 to 0.78	ρ = 0.6	0.37 to 0.76	ρ = 0.6	0.36 to 0.76
LT6	ρ = 0.68	0.48 to 0.81	r = 0.76	0.6 to 0.86	ρ = 0.76	0.59 to 0.86
LT7	r = 0.74	0.57 to 0.85	r = 0.77	0.62 to 0.87	ρ = 0.61	0.39 to 0.77

Note: LT1 = D_{max}; LT2 = Modified D_{max}; LT3 = Lactate concentration of 2 $mmol \cdot L^{-1}$; LT4 = Lactate concentration of 4 $mmol \cdot L^{-1}$; LT5 = Initial rise in lactate concentration of 1 $mmol \cdot L^{-1}$ above baseline; LT6 = Initial rise in lactate concentration of 2 $mmol \cdot L^{-1}$ above baseline; LT7 = Lactate increase of 1.5 $mmol \cdot L^{-1}$ above the point of minimum ratio between lactate and work rate.

DISCUSSION

To the best of the authors' knowledge, this has been the first study to assess the relationship between FTP and seven different lactate landmarks in a sample of road cyclists with a wide range of cardiorespiratory fitness levels. The main findings were as follows: a) there were significant differences in both PO and RPO measured at FTP compared to LT3 and LT5; b) large to near perfect correlations were found between PO, RPO and cadence measured at FTP and the same variables obtained at LT1, LT2 and LT4.

As many as 25 different lactate landmarks have been proposed in literature, though no consensus seems to exist regarding the relationships between them (7). In this study, there were significant differences ($p < 0.001$) between PO and RPO measured at FTP, and the same variables measured at fixed blood lactate concentrations of 2 $mmol \cdot L^{-1}$ and lactate increases of 1 $mmol \cdot L^{-1}$ above baseline. These findings have been reported in three previous studies, with differences as high as 7.5% between PO at FTP and at these two lactate landmarks (8,12,20). It should be remarked, however, that in these three studies FTP was established from an 8-minute test. To date, no previous research has assessed the differences between PO at FTP estimated from a 20-minute test and PO at fixed blood lactate concentrations of 2 $mmol \cdot L^{-1}$. The findings of this study suggest that FTP obtained through 20-minute testing is located at higher intensities that these two lactate landmarks.

It has previously been demonstrated that submaximal parameters such as LTs are key determinants of endurance performance (18). Therefore, providing evidence of the relationship between field-based tests and these endurance performance determinants shows the validity for such a test as a predictor of endurance performance. In the current study, there were large to near perfect correlations between PO, RPO and cadence at FTP and lactate thresholds established through D_{max} and modified D_{max} methods (see Table 1). Both methods have been previously compared to the FTP with varying degrees of success: McGrath et al., also found very large correlations between PO at FTP and PO at D_{max} in a sample of highly trained cyclists and triathletes (r = 0.89)(14). Likewise, Valenzuela et al. reported near perfect correlations (r = 0.95) for the D_{max} method in a sample including recreational and trained cyclists (23). However, contrary results have also been reported: Sanders et al. showed that PO at FTP was moderately to very largely different from PO at D_{max} and modified D_{max} (20) and Jeffries et al. found significant differences ($p < 0.05$) in PO at FTP obtained through 20-minute testing, D_{max} and modified D_{max} methods (10). The sample size used in the current study has been the largest to date and the results reflect the correlations found in previous studies that used the 20-minute test (14,23). The discrepancies found in other studies could therefore be related to the differences in sample characteristics, methods used for estimating FTP or even the testing protocols (10, 20).

Lastly, large to very near perfect correlations were also found for PO, RPO and cadence at FTP and the lactate threshold established at a fixed lactate concentration of 4 $mmol \cdot L^{-1}$. (r = 0.68- 0.93). Although similar results have been reported previously in the literature, the practical significance of this finding remains controversial. Gavin et al. found no significant differences between FTP estimated from an 8-minute test and this lactate threshold (8). Further, Jeffries et al. reported a very large correlation (r = 0.88) for this same threshold and FTP obtained from the 20-minute test (10). On the contrary, Sanders et al. showed moderate differences between PO at FTP obtained from an 8-minute test and this landmark (20). Despite these findings, it is well known that establishing thresholds at fixed blood lactate levels does not take into account the considerable inter-individual differences in lactate metabolism and may overestimate or underestimate the lactate threshold, which shows great variability among individuals (from 2–8 mmol·L^{-1}). Therefore, this finding remains anecdotal, as relying on fixed values for determining the lactate threshold is no longer accepted in the practical field (21). The correlations between cadence at several lactate landmarks and FTP found in the current study could also be highlighted. This finding can be explained by the fact that PO is dependent upon two factors: torque and angular velocity of the crank arm (3). Given that the freely chosen cadence normally increases with higher power demands, relationships between PO and cadence are to be expected (24).

The current study has shown large to very large relationships between PO at FTP estimated from a 20-minute test and PO at several commonly used lactate landmarks. Its major strength is the relatively large sample size when compared to previous similar studies (21). Further, the sample was composed by participants characterized by a wide range of fitness levels (from recreational to World Tour cyclists). This emphasizes the fact that the correlations obtained could be applied to broad cycling populations. However, the confidence intervals obtained in this study suggest caution when intending to use FTP and LTs interchangeably. As data suggest, several lactate landmarks can be linked to different wattages. As it stands, the broad range of LTs established in the literature may not even refer to the same physiological concept according to the results reported in the current study.

The correlations reported in this study were tested only in a road cycling sample. It is unknown whether these relationships between FTP and lactate thresholds would appear in other cycling disciplines characterized by higher anaerobic contributions such as cyclocross or mountain biking. Normally, these disciplines require mean power outputs that are in the FTP range but, at the same time, are produced differently than in road cycling. Accordingly, although FTP is still a relevant performance factor in these cases, lactate thresholds established through constant-load exercise may not be the best performance predictor for intervallic efforts. The verification of this relationship in highly intermittent disciplines could represent an interesting research area for the future.

PRACTICAL APPLICATIONS

Lactate thresholds are commonly used in the practical field to assess training load and performance and to prepare pacing strategies during competitive events. Given the results reported in this study, cyclists and coaches could use the power output at the FTP as a field alternative to lactate thresholds determined through dmax and modified dmax methods or calculated as a fixed blood lactate of 4 mmol·L^{-1}. Given the current broad availability of power meters and the reduced costs and time associated to power versus lactate testing, FTP could be proposed as a promising field alternative to these more expensive and complex assessments.

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6. Demandas fisiológicas y características de los participantes en un evento cicloturista

Physiological demands and characteristics of the participants

in a cycling sportive event

ABSTRACT

BACKGROUND: Cycling sportives have become increasingly popular in the last years. With over 11000 participants, the Quebrantahuesos (Qh), is one of the most prominent cycling events in Europe and its ever-growing competitive nature has increased the physiological demands required to obtain a great result. The objectives of the current study were to determine the relationship between the power profile and the result in the event as well as to describe the physiological differences among subgroups of participants according to their result.

METHODS: Ninety-one male cyclists took part in the study. Data regarding weight, height, experience and training volume were collected before the event. The raw data from the power meter used by the participants during the event's four climbs was sent to the researchers as an Excel file. Participants were then divided in three different groups according to their performance. One-way analysis of variance was performed to assess differences between groups. Pearson's product-moment correlation coefficient was used to assess for associations among performance and/or anthropometric data.

RESULTS: Group differences were found in body weight ($p < 0.001$), body mass index ($p < 0.001$), training volume ($p < 0.001$) and previous participations in the event ($p < 0.001$). A very high negative correlation between relative power during the climbs and the final time was also observed ($r > -0.92$; $p < 0.001$).

CONCLUSIONS: Better performances were associated to lower body weight and body mass index and higher training volume, relative power and experience. The current study provides data that suggests that as long as the average relative power is sustained, the pacing strategy throughout the different climbs does not affect the race outcome. This information could be used by cyclists and coaches when preparing the pacing strategy for the event.

*Keywords***:** *Cycling; Power meter; Relative power; Training; Quebrantahuesos*

Introduction

Road cycling is a very popular endurance sport characterized by its cyclic nature, variable intensity and high energetic demands[1]. The existence of the Tour de France as one of the most viewed sporting events around the world supports this fact. The popularity increase that endurance sports have seen during the last years can also be confirmed by the creation of a growing number of non-professional events such as cycling sportives[2]. The Qh or "Bone-Breaker" in Spanish is one of the most popular cycling sportives in the European calendar and the biggest cycling event in the Iberian Peninsula with more than 11000 participants from 24 different countries and over 14000 applications each year[3]. The route is composed by almost 200 km with 4 different climbs that sum up to 3500 meters of elevation gain. The competitive nature that the event has acquired during the last years has contributed to the increase in the utilization of professional and individualized training plans and even doping regimes among the participants in order to increase performance[4,5].

Road cycling, as any other sport discipline, requires constant and trustworthy means of monitoring training load in order to optimize performance[6]. As a consequence of this, several different instruments have been developed, among which power meters are the state of the art in the sport of cycling[7]. High values of absolute and relative power are considered a reliable indicator of road cycling performance[8]. Power meters have been consistently used in the professional field for a long time and, as it usually occurs, the last decade has seen a dramatic increase in the utilization of these tools by the amateurs[9].

Power meters are an objective mean of assessing training load and allow for the registration of the best power results (in watts) for each time period, which subsequently can be used in order to follow up some of the athlete's traits: neuromuscular, anaerobic, $VO2_{max}$ and threshold values, among others[7,8]. These tools measure power directly in the location where it is produced and, contrary to other training load assessment instruments used in endurance sports, do not take into account the physiological response to a workload, such as happens with heart rate monitors[10,11]. Data related to power output can be used to assess training load more objectively than with other traditional methods such as Training Impulse or Heart Rate Training Zone[6].

The utility of this measuring tool has been analyzed in the scientific literature during the last years [8]. Despite that, to the authors' knowledge, no previous study has investigated the power profile of the participants in a highly popular cycling sportive event. Furthermore, the authors have not found any previous study that had analyzed the physiological differences among the participants in a cycling sportive according to their final results, with special emphasis on their power profile. This information could be very valuable for athletes and coaches as it could represent an insight into the true physiological demands of such events and could provide objective information regarding the existing differences between those who perform well in cycling sportive events and the elite athletes. When the use of power meters became popular among professional cyclists, the information regarding the power profile of this particular subset of athletes became increasingly available[12-16]. The complexity of data analysis and the relatively high cost of power meters delayed their appearance in the amateur field. As a consequence, to the authors' knowledge, there's a lack of previous research providing information regarding the power profile of amateur athletes and the requirements of popular amateur cycling sportive events. Due to this lack of data regarding amateur cyclists, it could be valuable to understand this subset of athletes before attempting to work with them. Therefore, understanding the power profile of different groups of amateur cyclists who participate in famous cycling sportive events could provide coaches, researchers and athletes relevant information for the classification, training and performance assessment of this subset of athletes.

Therefore, the objectives of the study were i) to determine the relationship between the power profile of an athlete and the final result in the event as well as its predictive value and, ii) to describe the physiological differences among different subgroups of participants according to their final result, obtaining data that could be compared to that commonly reported in professional cyclists.

Materials and methods

Research design

The study design was cross sectional. Data was collected on two separate days, 17th and 26th of June 2019. Once all participants agreed to take part in the study, data relative to height and the sporting background were collected. During the sporting event, which took place on June 23rd, 2019, the participants recorded power data from four different segments established on the main climbs: Somport from Canfranc-Estación (5,4 km of length, 6% Σ gradient), Marie Blanque from Escot (9,1 km of length, 7,8% Σ gradient), Portalet from Laruns (28,2 km of length, 5% Σ gradient) and Hoz de Jaca (2,2 km of length, 7,2% Σ gradient). The questionnaire about the final result in the event and the power data was filled in between 24th and 26th of June. The raw data from the power-meter was also sent to the researchers.

Participants

8500 participants with an average finishing time of 7.8 hours (range 7.18 hours) took part in the event. The sample (n = 91) was divided into three different subgroups according to their final time in the event. The groups were divided based on the times that are normally in themselves an objective for the participants: Gold Group (GG = 30 cyclists; < 6h), Silver Group (SG = 28 cyclists; < 7h) and Bronze Group (BG = 33 cyclists; < 8h). Data relative to these three groups can be seen in Table 1.

Table 1. Characteristics of the participants

	GG 6 (n = 30) 346.67 ± 7.33 min	**SG 7 (n = 28)** 396.5 ± 14.02 min	**BG 8 (n = 33)** 439.18 ± 6.62 min	**All (n = 91)** 395.55 ± 40.86 min	**ANOVA** p-value
Age (years)	29.4 ± 5.15 [23 - 35]	26.1 ± 3.22 [23 - 33]	31 ± 3.22 [26 - 38]	27.4 ± 7.23 [19 - 38]	
Body mass (Kg)	66.53 ± 7.56 [53 - 81] #	68.82 ± 7.98 [52 - 85] +	74.64 ± 8.06 [62 - 90] #*	70.18 ± 8.54 [52 - 90]	< 0.001
Height (cm)	176.47 ± 6.84 [163 - 191]	176.04 ± 6.55 [160 - 189]	177.39 ± 5.7 [164 - 189]	176.67 ± 6.31 [160 - 191]	0.69
Body Mass Index	21.31 ± 1.41 [19 - 24.72] #+	22.13 ± 1.32 [19.97 - 25.88] *+	23.72 ± 2.41 [19.66 - 29.37] * #	22.44 ± 2.07 [19 - 29.37]	< 0.001
Training (years)	7.73 ± 2.08 [4 - 13] #+	5.21 ± 2.06 [2 - 9]+	4.64 ± 2.74 [1 - 14] #	5.84 ± 2.68 [1 - 14]	< 0.001
Training (hours/week)	15.47 ± 3.14 [11 - 27]* #	12.82 ± 2.61 [8 - 20]*+	9.64 ± 1.78 [6 - 13]+ #	12.54 ± 3.51 [6 - 27]	< 0.001
Experience (races)	5.8 ± 1.63 [2 - 9] * #	3.07 ± 1.65 [1 - 7]+	2.67 ± 1.63 [1 - 8]+	3.82 ± 2.14 [1 - 9]	< 0.001

*$p<0.05$ between GG and SG groups; #$p<0.05$ between GG and BG groups; +$p<0.05$ between SG and BG groups. Data is expressed as mean (standard deviation)

Participants were contacted through an invitation letter sent via social networks and email. During the first contact, researchers provided information related to the objectives of the study, its anonymous nature and the minimum requisites for participation, which were as follows: i) having participated in the 2018 Qh edition, ii) being familiar with power meters as a training monitoring tool, iii) owning one of the power meters listed by the researchers, which can be seen in Table 2, and iv) being at least eighteen years old. All the participants were informed about the procedures of data collection and the benefits and risks of participating in the study. The study was designed according to the latest version of the Declaration of Helsinki (2008, updated version by Fortaleza, 2013) and was approved by the Ethical Research Committee of the Autonomous Region of Aragón, Spain (Reference number 10/2019).

Data collection questionnaire

The questionnaire was designed by the researchers in the *Google Forms* application. Data was collected at two different stages. After signing the agreement to participate in the study, cyclists received an email requesting them to provide data related to their anthropometric values (height) and experience as cyclists (years participating in cycling sportive events, weekly average training volume in hours and number of previous participations in the Qh). Three days after the event concluded, the participants filled another questionnaire with data related to their race day weight, final time and power meter values, again through *Google Forms*. Raw data from the power meter was also sent as an Excel file (Microsoft® Excel® 2011 for Mac. Version 14.7.1) in order to allow the researchers to confirm the results submitted in the questionnaire. Once all the data were collected, weight and height were treated in order to obtain Body Mass Index (BMI). Absolute power and weight were also treated in order to obtain relative power in each one of the segments and the average during the four climbs.

Requirement for power meter data collection

As a study inclusion criterion, subjects were required to use a power meter which had been previously validated in a laboratory setting. Participants received a list of admitted power meters that was based on a previously published study[17]. Furthermore, participants were asked to use the same power meter during the whole event and to provide the raw data as an Excel sheet.

Table 2. Power meters allowed during the Qh and validated in the study by Maier et al[13]

Manufacture	Country	Models	Position
SRM	Germany	Science, Dura Ace, FSA and XX1	Crank spider
Power Tap	USA	P1, G3, GS y SL	Pedals and wheel hub
Quarq	USA	XX1, SRAM red and Elsa	Crank spider
Stages Cycling	USA	XTR, Rival, Dura Ace, Carbon, Ultegra and XT.	Crank arm (left only)
Verve Cicling	Australia	InfoCrank	Crank arm (left and right)
power2max	Germany	FSA, Ultegra	Crank spider
Garmin	USA	Vector	Pedals
Polar	Finland	Kèo Power	Pedals
Rotor	Spain	Power	Crank arm (left and right)

Statistical analyses

Mean and standard deviation (± SD) and range [min – max) were calculated for each variable. Normality and homoscedasticity were confirmed with the Kolmogorov – Smirnov and Levene tests. Differences between groups were analyzed with a one-way analysis of variance. When differences between groups were statistically significant, a post-hoc analysis was performed using t-student test for paired samples with the Bonferroni correction. Correlations between race time and relative power output were assessed using Pearson's product-moment coefficient of correlation (r) and the R-squared (R^2). Coefficients of correlation were reported together with their 95% confidence of interval (IC 95%). Statistically significant differences were considered when $p < 0.05$. All tests were performed in R v 3.5.1 (R Core Team, 2018) [18].

Results

Ninety-one male cyclists that participated in the Qh 2019 took part in the study. The mean ± SD values of the study sample were as follows: (age = 27.4 ± 7.23 years, weight = 70.18 ± 8.54 kg, height = 176.67 ± 6.31 cm, body mass index = 22.44 ± 2.07 kg/m^2, weekly training hours = 12.54 ± 3.51h and years of training experience = 5.84 ± 2.68 years) (Table 1).

The main characteristics according to the final time (GG, SG and BG) can also be seen in Table 1. BMI and average weekly training hours were statistically different among the three groups ($p < 0.05$). The BG (74.64 ± 8.06 kg) reported a significantly higher weight than the GG (66.53 ± 7.56) and SG (68.82 ± 7.98). Those who finished the event in less than 6h had participated in more previous editions of the Qh (5.8 ± 1.63 ; $p < 0.05$) and other cycling sportives than those who finished in less than 7h (3.0 ± 1.65 ; $p < 0.05$) and 8h (2.67 ± 6.62 ; $p < 0.05$). No significant differences in height were seen between the groups.

Power during the climbs and its average can be seen in Table 3. A very high negative correlation was found between the power output and the final event result (all $r > -0.92$; $R^2 = 0.7$; $p < 0.001$) (Table 4). The correlation between relative power averaged during the climbs and the final time can be seen in Figure 1. A predictive linear regression model for the final time according to the averaged watts per kilo is provided in Figure 1 ($r = -.92$; $p <$,001).

Table 3. Total and partial power values during the climbs.

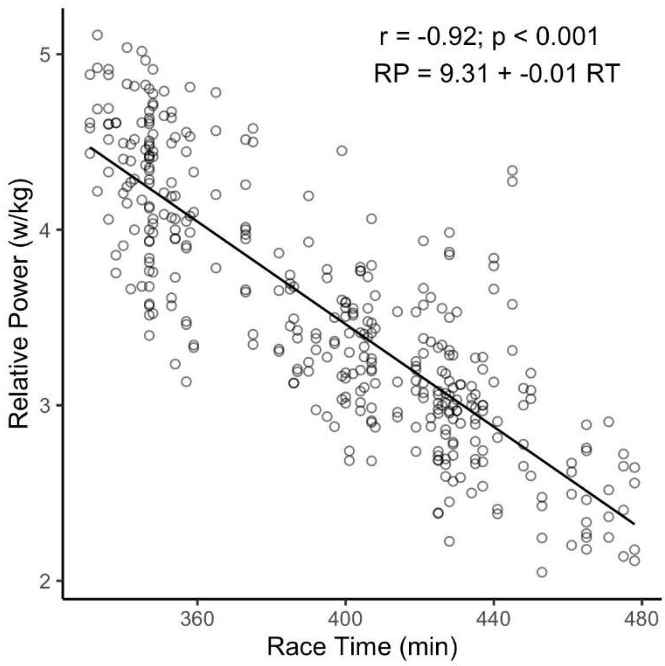
	GG 6 (n = 30)	SG 7 (n = 28)	BG 8 (n = 33)	All (n = 91)	ANOVA p value
Potencia relativa promedio (W/kg)	4.26 ± 0.28*#	3.44 ± 0.33*+	2.93 ± 0.38#+	3.53 ± 0.65	< 0.001
Port 1: Somport (w/kg)	4.49 ± 0.22*#	3.63 ± 0.44*+	3.06 ± 0.40#+	3.71 ± 0.70	< 0.001
Port 2: Marie Blanque (w/kg)	4.59 ± 0.31*#	3.70 ± 0.37*+	3.17 ± 0.43#+	3.80 ± 0.70	< 0.001
Port 3: Portalet (w/kg)	3.89 ± 0.36*#	3.18 ± 0.21*+	2.62 ± 0.38#+	3.21 ± 0.64	< 0.001
Port 4: Hoz de Jaca (w/kg)	4.07 ± 0.42*#	3.27 ± 0.35*+	2.86 ± 0.41#+	3.39 ± 0.65	< 0.001

*p<0.05 between GG and SG groups; #p<0.05 between GG and BG groups; +p<0.05 between SG and BG. Data is expressed as mean (standard deviation)

Table 4. Correlations between race time and power output.

	Race time (min)
Total Power Output (w/kg)	$r = -.92$; $p < .001$ (95% CI -.95 to -.88)
Partial Power Outputs	
Port 1: Somport (w/kg)	$r = -.90$; $p < .001$ (95% CI -.93 to -.85)
Port 2: Marie Blanque (w/kg)	$r = -.90$; $p < .001$ (95% CI -.93 to -.85)
Port 3: Portalet (w/kg)	$r = -.89$; $p < .001$ (95% CI -.93 to -.84)
Port 4: Hoz de Jaca (w/kg)	$r = -.86$; $p < .001$ (95% CI -.91 to -.80)

Figure 1. Correlations between average relative power and race time



Discussion

To the authors' knowledge this is the first study that has analyzed anthropometric, experience and absolute and relative power data of a large sample of participants in a well-known cycling sportive event (Qh). The main findings of the present study were as follows: i) The best performing group presented lower body weight and BMI together with higher training volumes and experience in this and other cycling sportives; ii) relative power reported in each one of the climbs as well as average power was inversely associated with the time result ($r > -0.92$; $p < 0.001$); iii) participants belonging to the highest performing group registered power values that are relatively close to those observed during the mountain stages of the grand tours in professional cycling; iv) a linear regression between relative power and final time is provided so athletes and coaches can predict performance before the event (r = -.92; p < .001) and v) when average relative power output remained the same, the differences in pacing among the four climbs did not influence the final results.

Road cycling is a sport discipline in which relative power is fundamental for optimal performance[19]. Considering the large elevation gain in the event (more than 3000 meters) it is not surprising that those who reported the best performance presented lower weight and BMI. Furthermore, higher training volumes were reported with participants who obtained better results ($p < 0.005$). This finding is being frequently reported in the literature and is in accordance with Seiler's theory that larger training volumes are positively related to better performance in these sport disciplines[21,22]. As more experienced riders obtained better results ($p < 0.005$), it could be suggested that a better knowledge of the route, ability while riding in the peloton and optimal concentration and rhythm management could be some of the positive factors provided by previous experience[23].

To the authors' knowledge only two previous studies have analyzed variables of the Qh participants[24,25]. Therefore, the results obtained in the present study are difficult to compare with those of other samples. Casterad et al., obtained higher weight values than those in the present study in a sample of 13 participants[24]. No power meter values were collected, and the height values were similar to those reported in this study. A more recent study again reported higher weight and similar height values, with no power meter data collection[25]. Given that previous research on this topic is scarce, the differences in height, weight, training volume and experience among the three groups of the current study could be used in order to set thresholds when differentiating between well and poorly trained cyclists in future research.

Regarding the relationship between relative power and final result it should be remarked that as long as the absolute power does not change, lower body weight will result in faster ascents. Equally, if the weight does not change, an increase in absolute power will inevitably transfer into higher speed. According to the results (Table 1), a mean of 4,26 w/kg was registered in the GG (>6h). Surprisingly, these values are only slightly lower than those reported during the mountain stages of the Giro D'Italia in a sample of 9 professional cyclists (a mean of 4.67 ± 0.45 w/kg)[8]. This value reflects the high level that is necessary in order to achieve an under 6 hours result in the event. Furthermore, when these results are analyzed in the power profile chart proposed by Allen and Coggan, the term "very good" would be used for power values between 4,2 to 4,8 w/kg for the Functional Threshold Power (FTP)[11]. This profiling, which has not been previously performed on a large sample of amateur cyclists, would demonstrate the increasingly high level that is necessary in order to achieve a good result in cycling sportive events. It could also be used in future studies as one of the references for setting a threshold for differentiating highly competitive amateur cyclists from professional athletes based on their power profile.

The main finding of the study was the determination of a linear regression model for the prediction of the final result according to the mean relative power values (Figure 1). Although data dispersion is large, this correlation allows the determination of the minimal requirements in order to achieve a specific result. Therefore, an average of 2.93 w/kg is necessary in order to achieve a sub-8h result (BG). The requirements increase slightly to 3.44 w/kg for a sub-7h result (SG) and even more, to 4.26 w/kg for the sub-6h (GG). According to the classification proposed by Allen and Coggan, the BG would be categorized as "untrained", the group SG as "normal to moderate" and the group GG as "moderate to very good"[11]. This classification, however, may result slightly erroneous as Allen and Coggan refer to the Functional Threshold power, which is theoretically the maximal power that a rider can sustain in an effort of around 40 minutes. In the Qh, however, these efforts are sustained after several hours of riding, commonly in a fast peloton. Furthermore, the efforts are unequal in length, with Portalet taking between 75 and 120 minutes to climb while Hoz de Jaca is an 8 to 13-minute effort for most of the riders. Therefore, caution is required when comparing the results obtained in the present study with commonly reported power chart values.

The correlation presented in the study allows for the design of pacing strategies during the event and for the prediction of the performance according to the relative power values (Figure 1. RP = 9.31 + -0.01Rt). As it is known, pacing with a power meter is normally more effective than subjective management of effort[26]. Therefore, the results reported may help coaches and athletes to objectively assess pacing and performance. It should be remarked that these target power ranges are only for this specific event and the four climbing segments that have been analyzed. The authors decided that other values related to the entire event such as average or normalized power would not reflect performance as clearly as they are more prone to be affected by confounding factors such as wind, tactical movements on the flat sections and especially drafting[27].

Finally, the low incidence of power variation between the climbs on the final result should be highlighted ($r = 0.06$; $p = 0.587$). This value suggests that while the mean power output necessary is maintained among the climbs, the variation of the power distribution will not affect the final result. This may have an influence on the strategy followed during the event, both with participants that prefer a more homogenous rhythm, and those who prefer to adapt the intensity to the length of the effort on each climb. Independently of the strategy followed by the athlete, data suggests that the final result will be similar as long as the same relative power output is maintained. This could have important implications in the practical setting as the usual pacing strategies during these events are characterized by riding closer to the FTP during shorter efforts and at lower intensities during longer climbs[11]. The results of the present study suggest that maintaining the same power output during all the climbs will result in the same outcome. Since mental fatigue is one of the key factors affecting performance in long endurance events, the authors consider that easy to understand and simple to follow pacing strategies should always be preferred when preparing for a cycling sportive[28].

The authors acknowledge that the study has several limitations. First, no women answered the questionnaire, which contrasts with the fact that 8% of the participants are of this gender[15]. Although this allows for better data homogeneity, the presence of a gender bias which fails to represent the real proportion of participants is an important limitation. Data was collected through self-reported questionnaires, which have several well-known limitations such as response bias and inaccurate reporting due to the retrospective nature of the evaluation. As no previous study exists around this topic, the questionnaire designed by the researchers has not been validated previously. An important limitation of the linear regression model is the fact that it includes all the contextual variables registered during the 2019 event. Because of that, every new variation (e.g. drafting, wind and environmental conditions during the day) during future editions may produce a slightly different final time even with the same power values as in the 2019 event. One of the main purposes of assessing only the climbing sectors of the event was to limit the affection of confounding factors such as weather conditions, tactical movements and drafting[27]. Therefore, other factors must always be taken into account when attempting to provide an estimate of the final result based on the wattage achieved on the climbs. One of the main objectives of the study was to recruit a large enough sample (n = 91) so the linear regression model could be trustworthy. This proved a disadvantage due to the fact that each of the riders had to ride the event with his own power meter. Therefore, different tools were used for power data registration, although all of the ones allowed in this study have been validated and were described as precise and reliable in a laboratory setting[17]. Finally, it must be remarked that the power profile obtained in the present study was collected during four different climbs throughout an endurance event. Therefore, caution is required when attempting to compare these results with the profiling provided by Allen and Coggan, which is normally performed in a controlled environment (reduced previous fatigue, weather conditions, etc).

Conclusions

This has been the first study that analyzed power, anthropometric, training and experience values in a segmented sample of participants in a popular cycling sportive such as the Qh. The main findings of the study were that: a) The best performing group presented lower body weight and BMI together with higher training volumes and experience in cycling sportives; b) relative power reported in each one of the climbs as well as average power was inversely associated with the time result; c) participants belonging to the highest performing group registered power values that are relatively close to those observed during the mountain stages of the grand tours in professional cycling; d) a linear regression between relative power and final time was provided so athletes and coaches can predict performance before the event and e) when average relative power output remained the same, the differences in pacing throughout the four climbs did not influence the final results. The information obtained in the current study could be used by researchers, cyclists and coaches in order to plan pacing strategies, assess performance and categorize groups according to their power profile. Future studies should recruit samples that would correctly represent the gender distribution in these events. Furthermore, the data obtained in this study should be compared with other samples analyzed in other international amateur events. The utilization of the same power meter by all the participants, direct anthropometric measuring and improved methods for assessing training load are some of the factors in order to further determine the validity of the results obtained in the present study.

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7. Discusión

El propósito principal de esta tesis doctoral fue determinar si el análisis de los datos extraídos a través de dispositivos de medición de potencia puede suponer una alternativa viable a la utilización de la información obtenida a través de los estudios clásicos de laboratorio. Los principales hallazgos fueron:

1) El UPF determinado a través de un test de 20 minutos se localiza a potencias que no difieren significativamente de la determinada en el PCR.
2) El UPF obtenido a través de un test de 20 minutos se localiza en valores que no difieren significativamente de la potencia asociada a la lactacidemia de 4mmol/L o a los umbrales de lactato determinados a través de los métodos Dmax y Dmax modificado.
3) El VO_{2max} de un ciclista de carretera puede ser estimado a partir de los datos de potencia relativa en un test de 5 minutos mediante la utilización de la fórmula: VO_{2max} = 16.6 + (8.87 * potencia relativa 5-min).
4) El rendimiento final del ciclista en uno de los principales eventos cicloturistas del mundo puede ser estimado a partir de los datos de potencia relativa obtenidos durante el ascenso de los diferentes puertos que configuran el evento.

Los tests incrementales de esfuerzo realizados en laboratorio se presentan como la manera más común y tradicional de valorar a deportistas de especialidades de resistencia. No obstante, están asociados a limitaciones que deben ser tenidas en cuenta, como el acceso a materiales de laboratorio y personal cualificado, los costes temporales y económicos asociados a la realización de las pruebas y la imposibilidad de analizar correctamente parámetros máximos y submáximos durante una misma sesión de valoración (Poole & Jones, 2017). Debido a estos limitantes, la posibilidad de analizar el rendimiento en el campo y sin necesidad de recurrir al laboratorio se vuelve una opción atractiva para entrenadores, ciclistas y científicos. En relación a ello, durante la última década los potenciómetros instalados en la propia bicicleta del deportista han ganado popularidad tanto en el campo profesional como en el aficionado (Passfield et al., 2017). Al contrario que la percepción subjetiva del esfuerzo, la velocidad o la FC, los valores de potencia son independientes de las circunstancias coyunturales propias del ciclismo de carretera (temperatura, calidad del asfalto, viento, etc) y por ello, permiten una valoración más objetiva de la carga a la que se somete el corredor. Además, el cada vez menor coste y la facilidad para la instalación de estos dispositivos de medición han convertido a esta herramienta como referencia para el control y valoración del rendimiento en ciclistas de carretera.

A pesar de la amplia implementación de los potenciómetros en el campo, el abordaje de esta herramienta desde el punto de vista científico ha sido escaso hasta la fecha. El análisis retrospectivo de la literatura científica en torno al entrenamiento por potencia en el ciclismo de carretera refleja las importantes limitaciones que caracterizaron a los estudios previos que intentaron determinar la posible relación existente entre parámetros obtenidos a partir de datos de potencia e hitos fisiológicos tradicionales extraídos en laboratorio. Tal como se relata en la revisión narrativa, hasta el momento no se había diseñado ningún test de campo para valorar el VO_{2max} de un ciclista entrenado en relación a la potencia desarrollada. Por otro lado, los estudios que habían valorado la propuesta de Coggan para el establecimiento del UPF lo habían hecho con muestras pequeñas, heterogéneas y en ocasiones sin implementar correctamente el protocolo original propuesto por los autores (Allen & Coggan, 2019; Borszcz et al., 2018; Borszcz et al., 2019; Inglis et al., 2019). Por estos motivos, los trabajos que componen esta tesis doctoral fueron diseñados para tratar de corregir las limitaciones observadas en estudios previos: se aplicó el protocolo íntegro de Coggan antes del test de 20 minutos y se incluyó una muestra más amplia y variada que las reportadas en estudios anteriores. Además, se incluyó un rango de niveles de muestra que abarcaban ciclistas desde desentrenados hasta profesionales.

La posibilidad de estimar el VO_{2max} y los umbrales submáximos a partir de datos de potencia resultaba atractiva y factible desde el punto de vista teórico. En este trabajo hemos demostrado que el VO_{2max} de un ciclista de carretera puede ser estimado a partir de sus datos de potencia relativa durante un test de 5 minutos de esfuerzo, prueba integrada dentro de la propuesta de protocolo establecido por Coggan (Allen & Coggan, 2019). Por otro lado, hemos verificado en una muestra mayor y con un rango superior en cuento a niveles de rendimiento entre sujetos, que el UPF estimado a partir del protocolo de Coggan se encuentra a intensidades que no difieren significativamente de las asociadas a marcadores clásicos propios de valoraciones de laboratorio como son el PCR, la lactacidemia fija de 4mmol/L o los umbrales de lactato establecidos a través de los métodos Dmax y Dmax modificado. Debido a que estos hitos fisiológicos se han relacionado estrechamente con el máximo estado estable metabólico a lo largo de la literatura científica, los resultados de los estudios presentados en este trabajo sugieren que el UPF calculado a partir de un test de 20 minutos puede ser una buena estimación de la intensidad asociada al máximo estado estable metabólico en ciclistas de carretera. Estos hallazgos son relevantes debido a que representan la posibilidad de evaluar los hitos fisiológicos más importantes estudiados de manera tradicional en el laboratorio a partir de la realización de un test de campo de poco más de una hora de duración. Esta posibilidad representa una ventana de oportunidad para entrenadores, científicos o ciclistas que no quieran o puedan permitirse las visitas recurrentes al laboratorio para la valoración del rendimiento de sus deportistas.

Finalmente, la última publicación de esta tesis doctoral representa la valoración de los datos de potencia obtenidos por una amplia muestra de ciclistas en uno de los eventos cicloturistas más importantes del calendario mundial, la Quebrantahuesos. Al igual que ya habían hecho otros autores previamente con otro tipo de eventos, se han analizado los datos de potencia de diferentes corredores con el fin de describir los requerimientos básicos para la finalización de la prueba en una determinada franja temporal y los requerimientos fisiológicos característicos del evento (Sanders & Heijboer, 2019; Pinot & Grappe, 2010; Sanders & Van Erp, 2019; Pinot & Grappe, 2011; Sanders et al., 2021; Pinot & Grappe, 2015; Van Erp & Sanders, 2020; Pinot & Grappe, 2017). Esta información representa otra aplicación clave del uso de potenciómetros en el campo: el conocimiento de los requerimientos fisiológicos de la prueba permite una mejor preparación de la misma, así como una predicción del rendimiento el día clave en base a los datos de potencia producidos por el deportista durante sus entrenamientos y eventos competitivos previos.

A pesar de las novedades que aportan las publicaciones asociadas a esta tesis doctoral y las aplicaciones prácticas derivadas de las mismas, cada uno de los trabajos descritos se ha caracterizado por sus propias limitaciones. En primer lugar, tanto los valores de VO_{2max} como los umbrales ventilatorios se han obtenido a través de pruebas incrementales de esfuerzo. Como ya se ha comentado en la introducción, este tipo de tests conllevan un posible riesgo de infraestimación del VO_{2max} y una posible sobreestimación de la potencia asociada a un determinado VO_2. Por otro lado, la determinación del UPF en base al protocolo de Coggan no supone el cálculo directo del UPF sino su mera estimación, aspecto que puede estar sujeto a error debido a que el comportamiento de la curva de potencia no es igual en todos los deportistas. En relación a los tests de lactato, debe ser tenido en cuenta que la medición de este parámetro durante un test incremental de esfuerzo no va a reportar valores iguales a los que se podrían obtener durante la aplicación de cargas fijas y estables, consecuencia de la propia naturaleza dinámica de los escalones del test. Finalmente, la predicción del rendimiento en la marcha cicloturista Quebrantahuesos se ha hecho en base a los datos de potencia de una única edición, por lo que extrapolar los mismos a la coyuntura de otros años puede suponer una fuente de error que debe ser tenida en cuenta, ya que circunstancias externas como temperatura, humedad, viento o lluvia pueden condicionar el tiempo final de la prueba a pesar de que se mantengan los mismos valores de potencia durante la misma.

Las limitaciones previamente mencionadas deberían ser resueltas por estudios futuros que: 1) verifiquen que el VO_{2max} alcanzado en las pruebas incrementales es realmente máximo; 2) tengan en cuenta el tiempo medio de respuesta y el componente lento del VO_2 a la hora de establecer los umbrales ventilatorios; 3) identifiquen el UPF a través de la curva de potencia del deportista y no un test indirecto como el propuesto por Coggan y 4) evalúen los datos de potencia de los eventos durante varias ediciones consecutivas para integrar en las predicciones las diversas coyunturas que pueden darse.

8. Conclusiones

A pesar del aumento en el uso de potenciómetros tanto en el ciclismo profesional como en el aficionado, el análisis científico de los datos de potencia obtenidos en tests de campo había sido limitado hasta la fecha. El compendio de publicaciones presentado en esta tesis doctoral ofrece información práctica que muestra la relación existente entre el PCR, la lactacidemia fija de 4mmol/L, el umbral de lactato estimado a partir de los métodos Dmax o Dmax modificado y el umbral de potencia funcional. Este trabajo provee además a entrenadores, ciclistas y científicos de una fórmula de estimación del VO_{2max} del ciclista en base a los datos de potencia de un test de campo. Finalmente, se presenta la posibilidad de predecir el rendimiento de un ciclista en un evento en base a sus datos de potencia desarrollados. La rápida integración de estas herramientas en el campo práctico supone una gran posibilidad para abrir futuras líneas de investigación que no necesariamente supongan la utilización del material y protocolos propios del laboratorio biomédico.

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10. Anexos

10.1 Consentimiento informado

DOCUMENTO DE CONSENTIMIENTO INFORMADO

Título del PROYECTO:

"***Descripción fisiológica y biomecánica del perfil de potencia y umbral funcional en ciclistas de alto nivel***".

Yo, ... (nombre y apellidos del participante)

He leído el documento de información que se me ha entregado.

He podido hacer preguntas sobre el estudio y he recibido suficiente información sobre el mismo.

He hablado con Isaac López, investigador responsable del proyecto.

Comprendo que mi participación es voluntaria.

Comprendo que puedo retirarme del estudio:

1) cuando quiera

2) sin tener que dar explicaciones

Presto libremente mi conformidad para participar en el estudio.

Deseo ser informado sobre los resultados del estudio: sí no (marque lo que proceda)

Si procede: Doy mi conformidad para que mis datos sean revisados por personal ajeno, para los fines del estudio y soy consciente de que este consentimiento es revocable.

He recibido una copia firmada de este Consentimiento Informado.

Firma del participante: ....

Fecha: ....

He explicado la naturaleza y el propósito del estudio al paciente mencionado

Firma del Investigador: ....

Fecha:

DOCUMENTO DE FE

Doy fe de la veracidad de los criterios que para este estudio se demandan como necesarios:

- No he padecido una lesión en los últimos seis meses que pueda alterar la toma de datos
- No he sufrido cirugía en los 12 meses previos a la toma de datos de este trabajo.
- No padezco dolor en la extremidad inferior o en el tronco en el momento de la realización del estudio.

Marque con una "x" los tres requisitos demandados en el caso de cumplirlos y firme el documento dando fe y veracidad a los mismos.

Firma del participante:

10.2 Autorización del comité ético

GOBIERNO DE ARAGON
Departamento de Sanidad

Informe Dictamen Favorable

C.P. - C.I. PI19/447

4 de diciembre de 2019

Dña. María González Hinjos, Secretaria del CEIC Aragón (CEICA)

CERTIFICA

1º. Que el CEIC Aragón (CEICA) en su reunión del día 04/12/2019, Acta Nº 21/2019 ha evaluado la modificación relevante referida al estudio:

Título: Descripción fisiológica y biomecánica del perfil de potencia y umbral funcional en ciclistas de alto nivel.

Investigador Principal: Isaac López Laval, Universidad de Zaragoza

Versión protocolo: Versión 2. 2_diciembre_2019
Versión documento de información y consentimiento: Versión 2. 2_diciembre_2019

2º. Considera que

- El proyecto se plantea siguiendo los requisitos de la Ley 14/2007, de 3 de julio, de Investigación Biomédica y su realización es pertinente.
- Se cumplen los requisitos necesarios de idoneidad del protocolo en relación con los objetivos del estudio y están justificados los riesgos y molestias previsibles para el sujeto.
- Es adecuada la utilización de los datos y los documentos para la obtención del consentimiento informado.
- El alcance de las compensaciones económicas previstas no interfiere con el respeto a los postulados éticos.
- La capacidad de los Investigadores y los medios disponibles son apropiados para llevar a cabo el estudio.

3º. Por lo que este CEIC emite **DICTAMEN FAVORABLE a la realización del estudio.**

Lo que firmo en Zaragoza

GONZALEZ HINJOS MARIA - DNI 03857456B
Firmado digitalmente por GONZALEZ HINJOS MARIA - DNI 03857456B
Fecha: 2019.12.10 15:01:13 +01'00'

María González Hinjos
Secretaria del CEIC Aragón (CEICA)

Página 1 de 1

Tel. 976 71 5836 Fax. 976 71 55 54 Correo electrónico mgonzalezh.ceic@aragon.es

10.3 Comunicación congreso

COLLEGE OF SPORTS AND HEALTH

11 Tose Jovanovica Street, 11030 Beograd, Serbia
Secretariat – phone no./fax: +381 11 7550 051
Student Services: +381 11 7550 162, +381 63 243 414
Web site: www.vss.edu.rs
E-mail: skola@vss.edu.rs

Confirmation of acceptance

We hereby confirm that the work authored by **Sebastian Sitko, Isaac López Laval, Rafel Cirer Sastre** entitled **"Physiological demands and characteristics of the participants in a cycling sportive event"** which is registered for the IV International Scientific Conference "Health, Sport, Recreation", which will be organized by the College of Sports and Health, to be held 14. May 2021 online in Belgrade, received a positive review and was accepted for publication in the Proceedings of the Conference.

Conference Organizing Committee
College of Sports and Healt

10.4 Cartas de aceptación

Publicación 1

Dear Dr. López Laval,

We are pleased to inform you that the following paper has been officially accepted for publication:

Manuscript ID: sustainability-819963
Type of manuscript: Review
Title: Power meters, power profile and functional threshold in road cycling
Authors: Sebatian Sitko, Rafel Cirer-Sastre, Francisco Corbi, Isaac López-Laval *
Received: 15 May 2020
E-mails: sebastiansitko@yahoo.es, rcirer@inefc.es, f@corbi.neoma.org, isaac@unizar.es
Submitted to section: Health and Sustainability,
https://www.mdpi.com/journal/sustainability/sections/health_sus
Physical Performance and Health Care for a Sustainable Lifestyle
https://www.mdpi.com/journal/sustainability/special_issues/sustainable_lifestyle
https://susy.mdpi.com/user/manuscripts/review_info/f109334a073d5046d84cde90ffc9ab32

We will now make the final preparations for publication, then return the manuscript to you for your approval.

If, however, extensive English edits are required to your manuscript, we will need to return the paper requesting improvements throughout.

We encourage you to set up your profile at SciProfiles.com, MDPI's researcher network platform. Articles you publish with MDPI will be linked to your SciProfiles page, where colleagues and peers will be able to see all of your publications, citations, as well as your other academic contributions.

We also invite you to contribute to Encyclopedia (https://encyclopedia.pub), a scholarly platform providing accurate information about the latest research results. You can adapt parts of your paper to provide valuable reference information for others in the field.

Kind regards,
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Publicación 2:

01-Apr-2021

Dear Professor Sitko,

It is a pleasure to accept your manuscript entitled "Five-minute power-based test to predict VO2max in road cycling" in its current form for publication in the International Journal of Sports Physiology and Performance. The comments of the reviewer(s) who reviewed your manuscript are included at the foot of this letter.

We anticipate that your paper will be published in print in approximately eight to ten months. The In Press and MedLine listings should be available well before that.

Thank you for your fine contribution. On behalf of the Editors of the International Journal of Sports Physiology and Performance, we look forward to your continued contributions to the Journal.

Yours sincerely,

Dr Stephen Cheung
Associate Editor, International Journal of Sports Physiology and Performance
stephen.cheung@brocku.ca

Publicación 3:

Dear Mr. Sebastian Sitko,

I am pleased to inform you that your manuscript entitled

Relationship between functional threshold power, ventilatory threshold and respiratory compensation point in road cycling

received by the editorial office of The Journal of Sports Medicine and Physical Fitness and registered under no. J Sports Med Phys Fitness-12285 has been accepted for publication as Original Article.

Before preparation of the proofs, the manuscript will undergo copy-editing to align it with the journal's editorial standards. You will be contacted by the editorial staff should any questions arise.

From now on, any request for substantial changes in content (changes of title and authorship, new results and corrected values, changes in figures and tables) will be subject to a completely new peer-review process.

Thank you for considering the journal The Journal of Sports Medicine and Physical Fitness for publication of your paper.

Sincerely,

Prof. Alberto Oliaro
Managing Editor
The Journal of Sports Medicine and Physical Fitness
....
Edizioni Minerva Medica
Corso Bramante 83-85
10126 Torino, Italy
Phone +39-011-678282, fax +39-011-674502
www.minervamedica.it

COMMENTS ON THE MANUSCRIPT
====================
Decision on manuscript
====================
Final decision: Accepted manuscript

Publicación 4:

CC: ratamess@tcnj.edu

Apr 24, 2021

RE: JSCR-08-16338R1, entitled "Functional threshold power as an alternative to lactate thresholds in road cycling"

Dear Dr. Sitko,

I am pleased to inform you of the official acceptance of your manuscript, JSCR-08-16338R1, entitled "Functional threshold power as an alternative to lactate thresholds in road cycling" for publication in the Journal of Strength and Conditioning Research. Congratulations to you and your co-authors in meeting the very high standard of quality that is required for publication in this Journal.

The production staff at Lippincott, Williams and Wilkins (LWW) will be sending galley proofs and work with you to put your manuscript into proper format for publication.

I want to take this opportunity to remind you to check the page proofs promptly and carefully for accuracy when you eventually receive them. You will receive them via email so please be attentive to such communications.

OPEN ACCESS

** Journal of Strength and Conditioning Research has recently transitioned to a new Open Access payment platform. If your manuscript was submitted prior to **March 9, 2021**, please contact the Journal of Strength and Conditioning Research Editorial Office. If your manuscript was submitted after **March 9, 2021**, please disregard this message. **

If you indicated in the revision stage that you would like your submission, if accepted, to be made open access, please go directly to step 2. If you have not yet indicated that you would like your accepted article to be open access, please follow the steps below to complete the process:
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Follow the JSCR on Twitter: @JSCRonline

We look forward to the submission of other manuscripts from your laboratory. Thank you for your contribution to the JSCR.

We wish you all the best in your future research projects.

Kind Regards,

Nicholas A. Ratamess, Ph.D., CSCS*D, FNSCA
Editor-In-Chief

Journal of Strength and Conditioning Research

Publicación 5:

Dear Mr. Sebastian Sitko,

I am pleased to inform you that your manuscript entitled

Physiological demands and characteristics of the participants in a cycling sportive event

received by the editorial office of The Journal of Sports Medicine and Physical Fitness and registered under no. J Sports Med Phys Fitness-10196 has been accepted for publication as Original Article.

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From now on, any request for substantial changes in content (changes of title and authorship, new results and corrected values, changes in figures and tables) will be subject to a completely new peer-review process.

Thank you for considering the journal The Journal of Sports Medicine and Physical Fitness for publication of your paper.

Sincerely,

Prof. Alberto Oliaro
Managing Editor
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www.minervamedica.it

COMMENTS ON THE MANUSCRIPT
====================
Decision on manuscript
====================
Final decision: Accepted manuscript

10.5 Artículo sobre el tono muscular en ciclistas de carretera

medicina

MDPI

Article

Characteristics of Pedaling Muscle Stiffness among Cyclists of Different Performance Levels

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Abstract: *Background and Objectives:* The aim of the present study was to compare the impact of an incremental exercise test on muscle stiffness in the rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), and gastrocnemius (GL) among road cyclists of three performance levels. *Materials and Methods:* The study group consisted of 35 cyclists grouped according to their performance level; elite ($n = 10$; professional license), sub-elite ($n = 12$; amateur license), and recreational ($n = 13$; cyclosportive license). Passive muscle stiffness was assessed using myometry before and after an incremental exercise test. *Results*: There was a significant correlation between time and category in the vastus lateralis with stiffness increases in the sub-elite ($p = 0.001$, Cohen's $d = 0.88$) and elite groups ($p = 0.003$, Cohen's $d = 0.72$), but not in the recreational group ($p = 0.085$). Stiffness increased over time in the knee extensors (RF, $p < 0.001$; VL, $p < 0.001$), but no changes were observed in the knee flexors (GL, $p = 0.63$, BF, $p = 0.052$). There were no baseline differences among the categories in any muscle. *Conclusions*: Although the performance level affected VL stiffness after an incremental exercise test, no differences in passive stiffness were observed among the main muscles implicated in pedaling in a resting state. Future research should assess whether this marker could be used to differentiate cyclists of varying fitness levels and its potential applicability for the monitoring of training load.

Keywords: cyclist; myometry; stiffness; incremental cycling test