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Evaluación del componente lento del consumo de oxígeno, la eficiencia ventilatoria y mecánica en los ejercicios con resistencias

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EVALUACIÓN DEL COMPONENTE LENTO DEL CONSUMO DE OXÍGENO, LA EFICIENCIA VENTILATORIA Y MECÁNICA EN LOS EJERCICIOS CON RESISTENCIAS

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Als meus fills, la Gael, l'Ibai, l'Aina i la Laia

Amat Victoria Curam

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Amor vincit omnia

LISTA DE ABREVIATURAS

1RM Una repetición máxima

ATP: Adenosintrifosfato

bLa Concentración de lactato en sangre

CMJ Salto con contramovimiento

CO_2: Dióxido de Carbono

CPET: Test de ejercicio cardiopulmonar

CPr: Fosfocreatina

CYC: Cicloergómetro

EE: Energía gastada/Gasto energético

FC: Frecuencia cardiaca

FC_{max}: Frecuencia cardiaca máxima

FR: Frecuencia respiratoria

GME: Eficiencia mecánica bruta

H^+: Iones de hidrógeno

HRV: Variabilidad del ritmo cardiaco

HS: Media sentadilla

HSE: Eficiencia de la media sentadilla

LT: Umbral de lactato

LT_1: Umbral de lactato 1 al 40-60% del VO_{2max} (ejercicio ligero)

LT_2: Umbral de lactato 2 al 60–90% de VO_{2max} (ejercicio de moderado a intenso)

MLSS: Máximo estado estable de lactato

O_2: Oxígeno

OBLA: Inicio de acumulación de lactato en sangre

OUES: Pendiente de la eficiencia del consumo de oxígeno

$P_{ET}CO_2$: Presión parcial del dióxido de carbono en la espiración

$P_{ET}O_2$: Presión parcial del oxígeno en la espiración

pH: Logaritmo negativo de base 10 de la actividad de los iones de hidrógeno

RER: Tasa de intercambio respiratorio

SBP: Presión sanguínea sistólica

VC: Volumen corriente

VCO_2: Volumen de dióxido de carbono

VE: Ventilación pulmonar

VE/VCO_2: Equivalente ventilatorio para el dióxido de carbono

VE/VO_2: Equivalente ventilatorio del oxígeno

VMR: Volumen minuto respiratorio

VO_2: Consumo de oxígeno

VO_{2max}: Consumo máximo de oxígeno

VO_{2SC}: Componente lento del consumo de oxígeno

RESUMEN DE LA TESIS DOCTORAL

INTRODUCCIÓN: El conocimiento del componente lento del consumo de oxígeno (VO_{2sc}), la eficiencia mecánica y ventilatoria, las respuestas metabólicas y cardiorrespiratorias y la fatiga mecánica en los ejercicios con resistencias en una prueba constante a intensidad de umbral láctico (LT) nos permite aumentar el rendimiento y descubrir el potencial de estos ejercicios en un metabolismo predominantemente aeróbico.

METODOLOGÍA: La tesis está compuesta por tres estudios experimentales. En el primer estudio se evaluó el VO_{2sc}, la energía gastada (EE) y la eficiencia mecánica (GME) en el ejercicio de media sentadilla (HS) en pruebas de carga constante a intensidad de LT. En el segundo estudio se comparó el VO_{2sc}, la eficiencia y/o economía, las respuestas metabólicas y la fatiga mecánica entre el cicloergómetro (CYC) y el ejercicio de HS durante una prueba de carga constante a una intensidad correspondiente al LT. En el tercer estudio se comparó las respuestas cardiorrespiratorias y la eficiencia ventilatoria, medida mediante el OUES y la pendiente del VE/VCO_2, entre el ejercicio de HS y del CYC en una prueba de carga constante a intensidad del LT. También se determinó la relación existente entre el OUES y la pendiente del VE/VCO_2 en ambas modalidades de ejercicio en cada participante. Se utilizó un protocolo de carga constante a intensidad de LT en el ejercicio con resistencia de HS y en el ejercicio de resistencia en CYC en adultos sanos. Se compararon las respuestas metabólicas, cardiorrespiratorias y la fatiga mecánica entre ambas modalidades de ejercicio.

RESULTADOS: En relación al VO_2 se observó un aumento significativo y sostenido en el ejercicio de HS ($p<0.05$) y un *steady-state* del VO_2 en el cicloergómetro. Por ello, se detectó un mayor VO_{2sc} en HS que en las pruebas de cicloergómetro al final del ejercicio ($p<0.05$). Se observó un gasto energético superior en el cicloergómetro que en la HS en cada punto de control ($p< 0.001$). Sin embargo, éste se mantuvo estable en el cicloergómetro y fue aumentando ligeramente a partir de la S3 en la HS ($p<0.05$). En relación a la fatiga en extremidades inferiores, se observaron pérdidas significativas entre el pre y post test en la altura del salto vertical ($p<0.001$), en la potencia media ($p=0.001$), y en la potencia pico ($p<0.010$) solo en el ejercicio de HS. La potencia máxima aumentó después de la prueba de cicloergómetro. Con respecto al análisis de la eficiencia ventilatoria, no se encontraron diferencias en la pendiente de la VE/VCO_2 y el OUES (*Oxygen Uptake Efficiency Slope*) entre ambos tipos de ejercicio ($p > 0.05$).

CONCLUSIONES: El VO_{2sc} y la EE incrementa en mayor medida a lo largo del ejercicio de la HS que en el ejercicio del CYC, ambos a carga constante a intensidad de LT. La eficiencia/economía es mayor en el ejercicio de la HS que en CYC. A pesar de que las respuestas cardiorrespiratorias fueron aumentadas en el ejercicio del cicloergómetro, la eficiencia ventilatoria fue igualmente eficaz en el ejercicio de HS que en el ejercicio en CYC en un metabolismo predominantemente aeróbico, lo que podría tener un impacto significativo en el ámbito clínico.

Palabras Clave: Cinética del consumo de oxígeno, umbral del lactato, fatiga mecánica, eficiencia mecánica bruta, gasto energético, media sentadilla, pendiente del equivalente ventilatorio del dióxido de carbono, pendiente de la eficiencia del consumo de oxígeno.

ABSTRACT

INTRODUCTION: Knowledge of the oxygen uptake slow component (VO_{2sc}), mechanical efficiency and ventilation, metabolic and cardiorespiratory responses and mechanical fatigue in resistance exercises allows us to increase performance and discover the potential of these exercises in a metabolism predominantly aerobic.

METHODOLOGY: This research consists of three experimental studies applying a protocol of constant-load to lactate threshold intensity in healthy adults in resistance exercises through half squats (HS), and in endurance exercises through cycle ergometer (CYC). The mechanical, cardiorespiratory and fatigue responses between both forms of exercise were compared.

RESULTS: Regarding VO_2, respiratory quotient and lactate response, a significant and sustained increase in VO_2 was observed in the HS exercise ($p <0.05$) and a stable VO_2 state from the cycle ergometer. In relation to VO_{2sc}, energy expenditure (EE), mechanical efficiency and economy, a mayor VO_{2sc} was observed in cycle ergometer than in the HS tests at the end of the year ($p <0.05$). A higher standard was observed in the cycle ergometer than in HS at each control point ($p> 0.001$) and from S3 in HS ($p <0.05$). Regarding fatigue in lower extremities, it was observed in the pre and post-test affecting the height of the jump ($p <0.001$), the average power ($p = 0.001$), and the peak power ($p <0.010$) only in the exercise of HS. The maximum power response was experimented after the cycle ergometer test. Regarding the slope of VE/VCO_2 and the Oxygen Uptake Efficiency Slope (OUES), no differences were found between both types of exercise ($p> 0.05$).

CONCLUSIONS: The HS exercise at a constant-load intensity of the useful life intensity induced an increase in VO_{2sc} than the exercise of the CYC. The efficiency/economy is greater in the exercise of the HS than in CYC. Although the cardiorespiratory responses were increased in the cycle ergometer exercise, ventilation was equally effective in the HS and CYC exercises in a predominantly aerobic metabolism, which could have a significant impact in the clinical field.

Keywords: oxygen uptake kinetics, lactate threshold, mechanical fatigue, gross mechanical efficiency, energy expended, half squat, oxygen uptake efficiency slope, slope of ventilation and carbon dioxide.

TABLA DE CONTENIDOS

1. INTRODUCCIÓN

1. INTRODUCCIÓN

El conocimiento de las respuestas cardiorrespiratorias al ejercicio ha sido motivo de multitud de estudios e investigaciones en el ámbito científico. Las respuestas cardiorrespiratorias agudas al ejercicio dependen, en gran medida, de la intensidad y de la duración de éste. Sin embargo, se ha constatado que otros factores derivados del modo de ejercicio también podrían condicionar las respuestas fisiológicas (1–3) afectando el metabolismo utilizado.

La variabilidad de estas respuestas cardiorrespiratorias no es más que una consecuencia de las características inherentes a cada modalidad de ejercicio (andar, correr, nadar, remar, etc.). Cada tipo de ejercicio produce una implicación diferente de la masa muscular, de la posición del cuerpo y de los grupos musculares efectores del movimiento que, conjuntamente con el nivel de actividad física y experiencia del sujeto, así como la comentada intensidad y duración del ejercicio, influyen y condicionan las respuestas cardiorrespiratorias (4–6). Por tanto, se podría reafirmar que las respuestas cardiorrespiratorias al ejercicio son dependientes del modo de ejercicio, la duración y la intensidad (7). El conocimiento de estas respuestas agudas es esencial para comprender los mecanismos adaptativos cardiorrespiratorios y metabólicos producidos por diferentes modalidades de ejercicio.

A pesar de la multitud de investigaciones que se han centrado en el análisis de las respuestas cardiorrespiratorias en los ejercicios de resistencia, muy poca información se ha reportado en los ejercicios con resistencias utilizados en las rutinas de entrenamiento para el desarrollo de la fuerza. Quizás porque estos han sido catalogados como estímulos anaeróbicos con características metabólicas que se alejan de los usuales ejercicios de resistencia (*running,* ciclismo, etc.) de más larga duración. Sin embargo, recientes estudios han abierto la posibilidad de reconducir el metabolismo anaeróbico característico de los ejercicios con resistencias hacia un metabolismo predominantemente aeróbico (8,9). Al respecto, el umbral láctico (LT) se ha convertido en una intensidad de ejercicio idónea para afrontar los mecanismos metabólicos derivados de los estímulos más puramente aeróbicos (10,11).

En base a lo comentado, el objeto de esta tesis doctoral es esclarecer y comparar los mecanismos fisiológicos, metabólicos y mecánicos subyacentes de ambos tipos de ejercicios en un metabolismo prioritariamente aeróbico: ejercicios de resistencia (*endurance exercise*) versus ejercicios con o contra resistencias (*resistance exercises*).

2. MARCO TEÓRICO

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2.1 Metabolismo

El metabolismo se define como el conjunto de intercambios físicos y químicos que permiten transferencias de energía y que se desarrollan en el organismo, incluyendo el crecimiento, el mantenimiento y las transformaciones físicas y químicas. El metabolismo implica dos procesos fundamentales: el anabolismo, definido como el proceso de construcción (como el aumento de la masa muscular), y el catabolismo, proceso de degradación (12). Todas las modalidades deportivas se realizan porque el ser humano tiene capacidad para extraer energía de los nutrientes (toda sustancia química utilizable por el organismo sin digestión previa), en especial de los glúcidos, lípidos y proteínas. La energía que extraemos de nuestra alimentación la transferimos a las proteínas contráctiles de los músculos implicados. La contracción muscular sólo es posible por esa transferencia de energía (12). El ser humano dispone de un intermediario entre la energía aportada por los alimentos y la energía para contraer los músculos. Este intermediario es un compuesto fosforado: el adenosintrifosfato (ATP), cuya rotura libera la energía que la célula muscular puede utilizar para contraerse. El ATP es un “intermediario de energía” entre la musculatura que se contrae y los alimentos que ingerimos y metabolizamos. Sin el ATP, la célula muere rápidamente, por lo que es indispensable para el organismo.

El ATP puede sintetizarse a partir del metabolismo anaeróbico láctico mediante la formación de lactato. El lactato se define como el metabolito resultante de la glucólisis que supera las posibilidades del metabolismo aerobio desarrollado en la mitocondria, procedente, por lo tanto, de la degradación incompleta de la glucosa (12). Su fórmula es: ($C_3H_6O_3$).

2.2 Gasto energético

El requerimiento de energía de una persona está relacionado con su gasto energético (EE) y se define como la energía que consume un organismo. Está representado por la tasa metabólica basal, la actividad física y la termogénesis inducida por la dieta (12).

El organismo necesita el aporte continuo de energía química para realizar sus diferentes funciones. Cualquier forma de trabajo biológico sólo es posible, al principio, mediante la transferencia directa de energía química en energía mecánica. Todos los gestos deportivos se realizan gracias a nuestra capacidad para extraer la energía de los nutrientes de nuestra alimentación, para transferirlos a las proteínas contráctiles de los músculos implicados. La contracción muscular solo es posible mediante dicha transferencia de energía. De manera que no es fácil definir lo que es energía, puesto que no es algo que posea dimensiones, unidad o masa (13).

La primera ley de la termodinámica estipula que la energía se conserva en sus distintas formas, de manera que no se crea, sino que se transforma. Según nuestra actividad, nuestras necesidades de energía adoptarán una u otra forma. Así, cuando nos movemos, la energía se halla en su forma mecánica y térmica, y el reposo permite reconstituir la energía química (13).

La cantidad de EE para diferentes actividades varía con la intensidad y el tipo de ejercicio. El coste energético de muchas actividades ha sido determinado, generalmente, controlando el consumo de oxígeno (VO_2) durante la actividad para determinar un consumo medio de oxígeno por unidad de tiempo. Las kilocalorías de energía usadas por minuto ($kcal.min^{-1}$) pueden calcularse entonces a partir de este valor.

2.3 Ácido láctico y lactato

A pesar del uso omnipresente del término “ácido láctico” en la comunidad científica y deportiva, se ha cuestionado la presencia real de cantidades significativas de ácido láctico en el cuerpo humano (14). Es cierto que la producción glucolítica de lactato está asociada con la producción de iones de hidrógeno (H^+). Sin embargo, esto no implica que el lactato sea la fuente de H^+, sino que la liberación de protones de la glucólisis está probablemente asociada con la hidrólisis no mitocondrial del ATP (15).

La molécula de energía ATP es necesaria para la contracción muscular. A medida que aumenta la duración del ejercicio, las reservas de fosfocreatina (PCr) disminuyen y el glucógeno muscular, o glucosa circulante en la sangre, se transporta a través de la vía glucolítica, formando ATP y piruvato. Tanto la glucólisis como la glucogenólisis producen el mismo número de piruvato, pero la glucólisis está asociada con la liberación neta de $2H^+$, mientras que la glucogenólisis produce solo $1H^+$, pero también un ATP adicional (15). Luego, el piruvato se transporta hacia las mitocondrias, donde sufre una fosforilación oxidativa, que produce una abundancia de ATP para permitir la contracción muscular en curso. A medida que aumenta la intensidad del ejercicio, las mitocondrias son incapaces de oxidar todo el piruvato disponible. Las concentraciones crecientes de piruvato desencadenan la conversión de piruvato a lactato a través de la enzima lactato deshidrogenasa (16) (Fig.1).

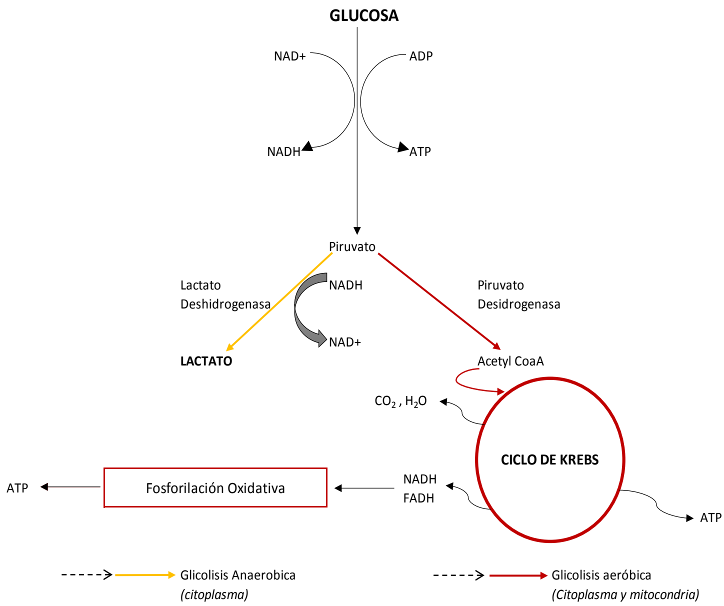

Figura 1. Degradación de la glucosa por la vía glucolítica y metabolismo del piruvato y su transformación en lactato

El lactato es un sustrato de energía vital, proporciona funciones clave en el metabolismo energético y es probable que funcione en la señalización celular durante el ejercicio. Además, el lactato no es responsable de la fatiga muscular, sino que es un importante sustrato energético que es utilizado por múltiples tejidos en todo el cuerpo y no se limita a las condiciones anaeróbicas. Los niveles de lactato en la sangre comenzarán a aumentar cuando la tasa de producción supere la tasa de absorción. Múltiples factores pueden contribuir a este aumento en el lactato sanguíneo, incluido el suministro de oxígeno, la capacidad mitocondrial y la capacidad de eliminar y utilizar el lactato por parte de otras células en todo el cuerpo (14).

2.4 Los ejercicios de resistencia

Conocidos en el ámbito científico como “*endurance exercises*”, son los comúnmente conocidos como ejercicios aeróbicos. Estos ejercicios de resistencia incluyen actividades prolongadas que aumentan la respiración y el ritmo cardíaco, como caminar, trotar, nadar e ir en bicicleta. Los ejercicios de resistencia que se abordan a continuación son: ejercicios de carga incremental y ejercicios de carga constante.

2.4.1 El ejercicio de carga incremental

La típica evaluación del ejercicio de carga incremental conocida como test de ejercicio cardiopulmonar (CPET) consiste en realizar una tarea e ir aumentando la intensidad de carga progresivamente, para pasar de un metabolismo aeróbico a un metabolismo anaeróbico hasta llegar a la extenuación. El CPET se ha convertido en el procedimiento de evaluación más común para evaluar objetivamente las respuestas cardíacas, ventilatorias y metabólicas en los ejercicios de resistencia como el ciclismo, la carrera, el ergómetro de brazos e incluso la natación. Estas respuestas son comparadas con los valores establecidos como de referencia en función de la edad, el sexo, las características antropométricas y el nivel de entrenamiento, determinando la capacidad funcional cardiorrespiratoria de los sujetos. El patrón general de respuesta durante el ejercicio incremental ha sido ampliamente estudiado desde hace muchos años (17–19).

2.4.1.1 El umbral láctico

La denominada transición aeróbico-anaeróbica puede servir como base para evaluar el rendimiento, así como para prescribir intensidades en el entrenamiento de resistencia (20).

Durante una prueba de resistencia incremental hay un punto en el cual las concentraciones de lactato (bLa) en sangre comienzan a aumentar por encima de los valores de reposo. Este momento metabólico fue descrito por unos autores como “umbral anaeróbico” (21) y por otros como “umbral aeróbico” (22), generando una confusión conceptual. Otros autores describen este cambio metabólico como el “inicio de la acumulación de lactato en sangre” (OBLA) (20).

Por otra parte, existe una máxima intensidad de ejercicio por encima de la cual un continuo aumento de bLa es inevitable, punto que ha sido considerado como el “umbral anaeróbico” (22,23).

Sin embargo, otros autores lo han denominado como “máximo estado estable de lactato” (MLSS) (20).

El MLSS se puede definir como la intensidad máxima del ejercicio que puede mantenerse durante un tiempo prolongado (>25 min), sin un incremento continuado (<1mmol/L) de la bLa (24). La determinación del MLSS se ha vuelto muy popular en el diagnóstico del rendimiento en varios deportes de resistencia. Se supone que el MLSS se puede utilizar para establecer la mayor carga de trabajo que se puede mantener a lo largo del tiempo sin una acumulación continua de lactato en la sangre. En sujetos entrenados, tanto en atletas de élite como en atletas juveniles, el MLSS ocurre a diferentes bLa en sangre para diferentes modos de ejercicio (24).

A pesar de la controversia que ha generado entre los diferentes autores el concepto de umbral aeróbico o anaeróbico, o en su defecto el de los umbrales lácticos o ventilatorios, se debe de considerar que se les denomine de una forma u otra ya que corresponden a un momento metabólico similar a partir del cual las bLa comienzan a incrementar en proporción a la intensidad de ejercicio planteada. Por tanto, el LT se define como la intensidad de ejercicio o VO_2 que precede inmediatamente al incremento inicial y continuo del lactato sanguíneo desde los valores de reposo (25).

Se han encontrado diferentes conceptos de LT, que han sido considerados en la categoría del umbral aeróbico. Las formas de determinar dicho LT son variadas según la diversa literatura científica (20).

El LT se determina de diferentes formas:

- Antes o cuando la bLa comienza a aumentar por encima del nivel de referencia (26,27).
- Cuando la bLa exhibe un marcado / sistemático / significativo / no lineal /aumento sostenido agudo / abrupto por encima de la línea del valor de base (22,26,28,29)
- La primera elevación significativa del nivel de lactato (aproximadamente 2 mmol/L) (22,30).
- Antes de una elevación en la bLa sobre la línea base (al menos 0,2 mmol/L debido a error del analizador de lactato) (31,32).
- Aumento del lactato delta (inicio de la acumulación de lactato en plasma) (33).
- En el equivalente mínimo de lactato (bLa dividido por la absorción de oxígeno o la intensidad de trabajo) (34,35).

- En la que la bLa en plasma comienza a aumentar cuando el log bLa se cruza con el log (intensidad de trabajo) (36).
- En el que la bLa aumenta 0,5 mmol/L por encima de los valores en reposo (37).
- En la que la bLa aumenta 1 mmol/L por encima de la línea de base (es decir, lactato a baja intensidad correspondiente al 40-60% VO_{2max}) (38,39).
- Precediendo un aumento de la bLa en 1mmol/L o más (40,41).

La respuesta del lactato en sangre al ejercicio ha sido comúnmente utilizada en los ejercicios de resistencia para evaluar parámetros de aptitud aeróbica como el LT, el umbral anaeróbico y el umbral ventilatorio (42). Estos umbrales han sido empleados como intensidad de referencia en los CPET en condiciones de laboratorio para valorar el fitness cardiorrespiratorio, la cinética del VO_2, la eficiencia mecánica y ventilatoria, tanto durante protocolos incrementales como constantes preferentemente en ejercicios de resistencia como el tapiz rodante, el cicloergómetro y el ergómetro de brazos (43–45). Además, estos umbrales son frecuentemente aplicados en la prescripción de la intensidad de ejercicio especialmente en actividades de resistencia como la carrera (42,43), el ciclismo, la natación (45) y el triatlón (46), y para prescribir ejercicio que garantice una eficacia óptima y una máxima seguridad a pacientes con enfermedades cardiovasculares, donde una intensidad de ejercicio por encima de un nivel crítico puede tener potenciales efectos perjudiciales (47).

La prescripción correcta del ejercicio se relaciona con el porcentaje de la intensidad relativa del ejercicio, la frecuencia cardíaca máxima (FC_{max}) o se vincula con el LT. Para la determinación del LT durante el ejercicio, básicamente se utilizan dos métodos diferentes: (i) medición invasiva directa del lactato sanguíneo o (ii) medición no invasiva de la respuesta de intercambio de gases y de la ventilación con definición indirecta del LT (47).

Una serie de estudios en pruebas incrementales han identificado la existencia de dos umbrales ventilatorios o umbrales de lactato. Desde el punto de vista fisiológico se pueden definir tres fases de suministro de energía y dos puntos de intersección al aumentar la intensidad del ejercicio, de acuerdo con el modelo trifásico de Skinner y McLellan (30). Se sugiere que al primer umbral se le llame “umbral aeróbico” y al segundo “umbral anaeróbico” (30).

En la primera fase, durante el ejercicio muy suave, existe un aumento lineal en el VO_2, en la producción del CO_2 (VCO_2) y en la ventilación. En esta fase hay una mayor extracción de O_2 por los tejidos, lo que da una fracción más baja de la presión parcial del O_2 ($P_{ET}O_2$) en el aire expirado. Por el contrario, se produce más VCO_2. La tasa de trabajo está entre 45-55% del consumo máximo de oxígeno (VO_{2max}), la frecuencia cardíaca (FC) está entre 60-70% de la FC_{max} y la bLa < 2mmol/L.

En la segunda fase, al aumentar la intensidad del ejercicio (55-80% VO_{2max}, 70-90% FC_{max}) la producción de lactato es mayor que la capacidad de metabolización en la célula muscular (2-4 mmol/L). El aumento de [H^+] es suavizado por el ion bicarbonato (HCO_3^-), lo que produce un aumento del VCO_2 y un aumento continuo de la presión parcial del CO_2 expirado ($P_{ET}CO_2$). Hay un aumento más pronunciado de la ventilación pulmonar (VE), mientras que el aumento del VO_2 sigue siendo lineal al aumentar la carga de trabajo. La capacidad oxidativa de todo el sistema es suficientemente alta para alcanzar el rango del lactato entrante. Durante el estado estable o estacionario (*steady-state*) aparece un equilibrio entre la producción y la absorción de lactato. La máxima carga de trabajo que se puede realizar (alrededor de 30') sin un aumento sistemático de la bLa se denomina MLSS y determina el segundo umbral anaeróbico (48–50).

En la tercera fase con una carga de trabajo por encima del segundo LT (>80% Vo_{2max} y >90% FC_{max}) la tasa de producción de lactato (>4 mmol/L) supera la tasa de eliminación sistemática del lactato. Esto conduce un aumento exponencial de la bLa durante el ejercicio incremental. Se observa un aumento no lineal adicional en el VCO_2, y más pronunciado en la VE. En este punto, la hiperventilación no puede compensar adecuadamente el aumento en la (H^+) y se produce una caída en la $P_{ET}CO_2$.

En la figura 2 se observan las tres fases de la relación entre la bLa y la intensidad del ejercicio.

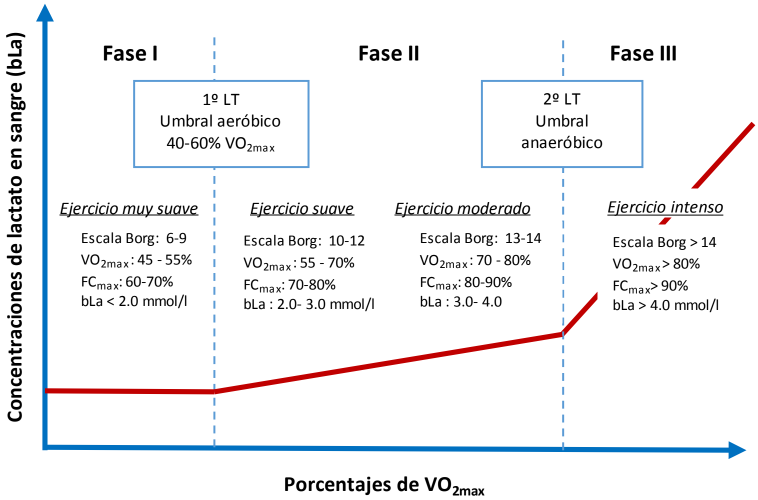

Figura 2. El modelo trifásico según Skinner et al. adaptado de Binder R.K. et al. (47): relación entre la concentración de lactato en sangre (bLa) y la intensidad del ejercicio. Frecuencia cardíaca; VO_{2max}: consumo máximo de oxígeno; Escala de Borg: valoración subjetiva del esfuerzo percibido.

2.4.1.2 Las respuestas cardiorrespiratorias agudas

En este apartado referente a las respuestas cardiorrespiratorias se abordan los siguientes conceptos: FC, VO_2 , VCO_2, VE y RER.

Nuestro sistema cardiovascular es capaz de adaptarse a los cambios que se establecen en dichas demandas para mantener de forma adecuada el equilibrio necesario para que nuestro organismo se mantenga vivo. Los cambios que experimenta constantemente nuestro sistema cardiovascular se hacen más patentes durante el ejercicio, situación de gran demanda metabólica por parte del tejido muscular.

La FC es el principal factor responsable del aumento del gasto cardíaco durante el ejercicio. A intensidades bajas de ejercicio, el aumento de la FC es casi el único responsable del aumento del gasto cardíaco, pues el volumen sistólico apenas se modifica. Durante el ejercicio dinámico, la FC aumenta de forma proporcional a la intensidad del ejercicio hasta llegar a la máxima intensidad, de manera que si estudiamos el comportamiento de este parámetro durante la realización de un ejercicio de tipo incremental en el laboratorio, obtenemos una relación lineal entre la intensidad y la FC hasta finalizar el ejercicio máximo (Figura 3) (25).

Utilizamos el término VO_2 para expresar un parámetro fisiológico que indica la cantidad de oxígeno que se consume o utiliza el organismo por unidad de tiempo. La medición directa o estimación indirecta de este parámetro permite la cuantificación del metabolismo energético, ya que el oxígeno se utiliza como comburente en todas las combustiones que tienen lugar en las células y que permiten la transformación de la energía química en energía mecánica y trabajo celular (25).

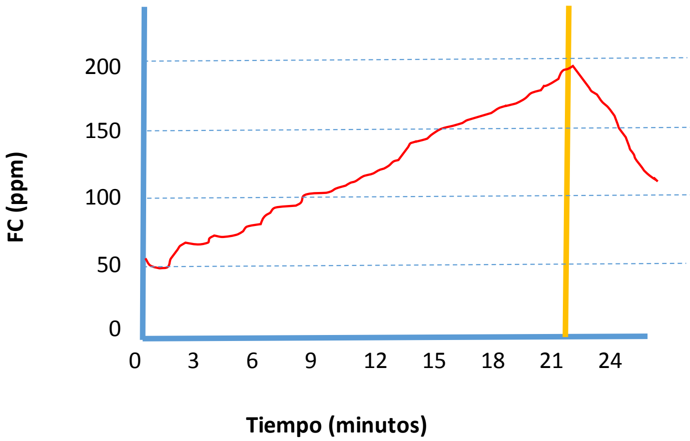

Figura 3. Representación real del comportamiento de la frecuencia cardíaca durante un ejercicio incremental hasta el agotamiento. Obsérvese el descenso brusco al finalizar el ejercicio. FC: Frecuencia cardíaca; ppm: pulsaciones por minuto. Adaptado de Chicharro et al. (25).

El VO_2 presenta una relación lineal con la intensidad del ejercicio. Esta relación mantiene su linealidad durante las cargas de trabajo submáximas, pero la pierde si el sujeto es capaz de aumentar la intensidad de ejercicio una vez que ha llegado a su VO_{2max}. En este caso, se producirá gráficamente una meseta; es decir, el VO_2 se mantendrá estable a pesar de que se aumente la intensidad del ejercicio (Figura 4).

Algunos autores defienden que la presencia del componente lento en la cinética del VO_2 implica que, durante una prueba de esfuerzo incremental, después de haber superado el LT, la relación entre el VO_2 y el trabajo realizado tiene que ser curvilínea (51).

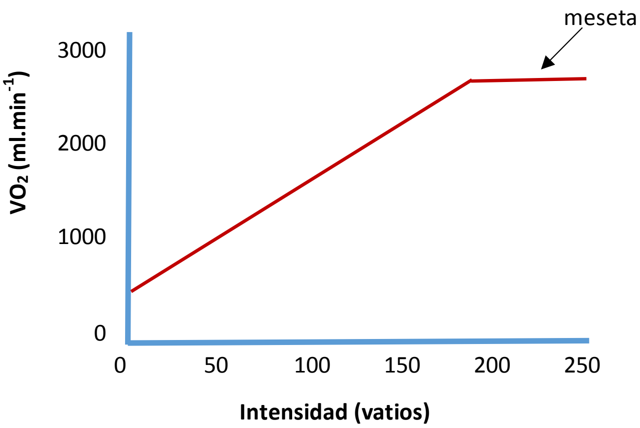

Figura 4. Respuesta del VO_2 durante la realización de un ejercicio incremental en rampa. Adaptado de Chicharro et al.(25).

La intensidad del trabajo a la cual se produce esta pérdida de proporcionalidad ha sido denominada punto de cambio en el VO_2. Esta cinética refleja una pérdida de eficiencia mecánica muscular, considerándose los siguientes factores como contribuyentes a este hecho: aumento de la VE, acumulación de lactato sanguíneo y de $[H^+]$, aumento en la concentración de catecolaminas plasmáticas, aumento de la temperatura muscular y reclutamiento de las fibras musculares tipo II (52).

Desde un punto de vista fisiológico las funciones básicas de la VE son:
1) el intercambio de O_2 y de CO_2 con el entorno
2) la regulación del pH de la sangre

Durante la realización de un ejercicio físico la ventilación debe aumentar con respecto a sus valores de reposo para permitir el transporte de oxígeno necesario a los tejidos activos por una parte y, por otra, para eliminar el VCO_2 generado en exceso por esos mismos tejidos. Así, la VE, que en estado de reposo es de aproximadamente 6 $l \cdot min^{-1}$, puede llegar a alcanzar durante un esfuerzo máximo aproximadamente los 90-100 $l \cdot min^{-1}$ en personas no entrenadas, y hasta más de 200 $l \cdot min^{-1}$ en sujetos altamente entrenados sometidos a un entrenamiento intenso de resistencia aeróbica.

Se identifican dos fases en la respuesta de la ventilación al ejercicio:

FASE I (Componente rápido): en la que la ventilación aumenta de forma brusca e inmediata. La justificación de este comportamiento de la ventilación radica en el sistema nervioso central, cuyos estímulos parecen gobernar esta fase de adaptación rápida. Esta respuesta ventilatoria precede a cualquier cambio químico en la composición de la sangre, demostrando con ello que no está asociada a aumentos de la tasa de intercambio respiratoria (RER), de la $P_{ET}O_2$, o con disminuciones de la $P_{ET}CO_2$ (25).

FASE II (Componente lento): en la que el ajuste de la ventilación es más gradual hasta llegar a la tasa requerida por el esfuerzo desarrollado. Durante esta fase las modificaciones de la ventilación sí están asociadas con las alteraciones en la presión parcial de los gases sanguíneos. Es una fase que podríamos considerar de adaptación lenta. Así, se observa un incremento de la $P_{ET}O_2$, y una disminución simultánea de la $P_{ET}CO_2$ (25).

La relación entre el volumen de aire espirado o ventilado y la cantidad de oxígeno que consumen los tejidos en un determinado periodo se denomina equivalente ventilatorio para el oxígeno (VE/VO_2). En adultos sanos, el cociente VE/VO_2 suele mantenerse alrededor de 25 (es decir, 25 litros de aire ventilado por litro de oxígeno consumido) en ejercicios realizados a una intensidad no superior al 55% del VO_{2max}.

Cuando el ejercicio desarrollado es de alta intensidad, el VE/VO_2 puede superar el valor de 30 litros de aire por litro de oxígeno consumido, reflejando con ello modificaciones en el equilibrio metabólico del organismo y también una menor eficiencia respiratoria; así, ventilar 1 l. de aire alveolar tiene un costo de oxígeno más elevado (25). Lógicamente, estos valores aproximativos dependerán del nivel de fitness cardiorrespiratorio de las personas.

En los alvéolos pulmonares tiene lugar el intercambio de O_2 y de CO_2 entre la atmósfera y la sangre, y por ello, gracias a la ventilación, la $P_{ET}O_2$ en los alvéolos es mayor que la existente en los tejidos metabólicamente activos o en la sangre venosa procedente de los mismos. Así, la ventilación permite que la $P_{ET}O_2$ se mantenga constante (alrededor de 105 mmHg), y que el O_2 se mueva desde los alvéolos a la sangre, para ser distribuido a los diferentes tejidos. A su vez, gracias a la ventilación pulmonar, la $P_{ET}CO_2$ se mantiene bastante baja en los alvéolos pulmonares (en torno a 40 mmHg), creando un gradiente de presiones negativo para que el CO_2 procedente del metabolismo celular se elimine desde los tejidos, a través de la sangre, hacia los alvéolos y, por tanto, hacia el exterior. Por todo ello, tanto la frecuencia de la respiración como la profundidad de la misma influyen sobre la cantidad de O_2 y de CO_2 que se intercambian entre el organismo y la atmósfera, y esto tiene especial importancia cuando realizamos ejercicio físico (25).

Si se conocen el VO_2 y el VCO_2, entonces es posible estimar el tipo de combustible que se utiliza para la oxidación. La cantidad de O_2 usado durante el metabolismo depende del tipo de combustible que se oxida. La calorimetría indirecta mide la cantidad de VCO_2 y de O_2 consumido. La proporción entre estos dos valores se denomina RER. La RER es la relación entre en volumen de CO_2 producido y el volumen de O_2 consumido por unidad de tiempo.

Las respuestas cardiorrespiratorias son diferentes dependiendo de la modalidad del ejercicio. Se han comparado las diferencias fisiológicas entre el ciclismo y la carrera, y a pesar de que en la cinta de correr el sujeto utiliza más masa muscular, la mayoría de los estudios indicaron que los corredores alcanzan un VO_{2max} más alto, mientras que los ciclistas entrenados pueden alcanzar un valor de VO_{2max} en cicloergómetro, similar al de la carrera en tapiz rodante. Se ha informado en dicho estudio diferencias en las respuestas ventilatorias al ejercicio (hipoxemia arterial inducida por el ejercicio, capacidad de difusión del oxígeno, fatiga ventilatoria y mecánica pulmonar) entre la carrera y el ciclismo, y la ventilación es más deficiente en el ciclismo que en la carrera, así como valores de FC a intensidades máximas y submáximas (53).

Los músculos pequeños o menos condicionados pueden limitar el ejercicio cuando el corazón y los pulmones no están estresados. La posición del cuerpo en el mismo ejercicio también tiene diferentes respuestas a nivel cardiorrespiratorio. En un estudio comparativo de las diferentes respuestas cardiorrespiratorias entre un cicloergómetro y un ejercicio de ergómetro de brazo, con cargas iguales de 50 W y 100 W, el ergómetro de brazo provocó una ventilación casi dos veces más alta que el cicloergómetro. La ventilación fue afectada por incrementos significativos tanto en la frecuencia cardíaca como en el volumen corriente. También se observaron respuestas más altas en el ergómetro de brazo en comparación con el cicloergómetro en el VO_2, el VCO_2, la FC y la bLA en sangre. Sin embargo, la presión arterial sistólica y el pulso tendieron a ser más bajos en el ergómetro de brazo que en el de piernas (54).

2.4.2 El ejercicio de carga constante

El CPET también ha sido ampliamente utilizado para evaluar las respuestas cardiorrespiratorias y metabólicas en el ejercicio a carga constante a diferentes intensidades. Este tipo de evaluación nos permite interpretar el comportamiento de los parámetros cardíacos, ventilatorios y metabólicos ante intensidades donde prevalece un metabolismo prioritariamente aeróbico, en el metabolismo de transición aeróbico-anaeróbico y en un metabolismo mayoritariamente anaeróbico.

2.4.2.1 El comportamiento del lactato

El entrenamiento de resistencia aumenta la carga a LT. Dicho de otro modo, después del entrenamiento podemos rendir a ritmos de esfuerzo más elevados y a un ritmo absoluto de VO_2 más alto sin elevación del lactato en sangre por encima de los valores en reposo. Este incremento del LT parece deberse a varios factores; entre ellos una mayor capacidad para eliminar el lactato producido en los músculos y un incremento de las enzimas de los músculos esqueléticos, junto con un cambio en el sustrato metabólico como consecuencia del entrenamiento. El resultado neto es una menor producción de lactato para la misma intensidad de esfuerzo (55). Por lo tanto, en el ejercicio a carga constante a LT, el comportamiento del lactato se mantiene estable.

Las concentraciones de lactato en sangre incrementan desde el inicio del ejercicio hasta una subida aproximada de entre 2 y 3 mmol/L y luego se mantienen estables. Se ha demostrado que tanto en los ejercicios a carga constante a LT de resistencia como en los ejercicios a carga constante a LT con resistencias, el comportamiento del lactato es estable en ambos (7).

2.4.2.2 Respuestas cardiorrespiratorias agudas

De la misma manera que en los ejercicios de resistencia incrementales, se aborda en este apartado referente a las respuestas cardiorrespiratorias, los mismos parámetros: FC, VO_2, VCO_2, VE y RER.

Las respuestas respiratorias (VO_2, VCO_2, VE, RER), en un estudio de Garnacho et al. (10), se elevaron significativamente en el primer momento del estudio (aproximadamente en el minuto 4) hasta que se alcanzó un estado estable que persistió hasta el final del ejercicio. Este comportamiento estable de las variables de intercambio de gases se observaron entre los minutos 10 y 30 de los ejercicios con resistencias (56) en pruebas de carga constante realizadas a una tasa de trabajo correspondiente al LT.

En dicho estudio en que se compararon ejercicios de resistencia versus ejercicios con resistencias, a pesar del estado estable, las respuestas respiratorias (excepto el RER) fueron significativamente mayores para el cicloergómetro que para el ejercicio del HS. En otros estudios se han detectado diferencias en las respuestas respiratorias a diferentes modalidades de ejercicio y se han reportado elevadas respuestas respiratorias para el ejercicio en tapiz rodante (1)y cicloergómetro (57).

Durante el ejercicio, se produce un incremento de la demanda de O_2 en los músculos activos a la vez que se utilizan una mayor cantidad de nutrientes. También se aceleran los procesos metabólicos, por lo que aumenta la generación de productos de desecho.

La FC aumenta desde el inicio del ejercicio de carga constante hasta el cuarto minuto, del minuto 4 al minuto 8,5, el aumento es ligero y a partir de éste se mantiene en valores estables hasta finalizar el ejercicio (Figura 5) (10).

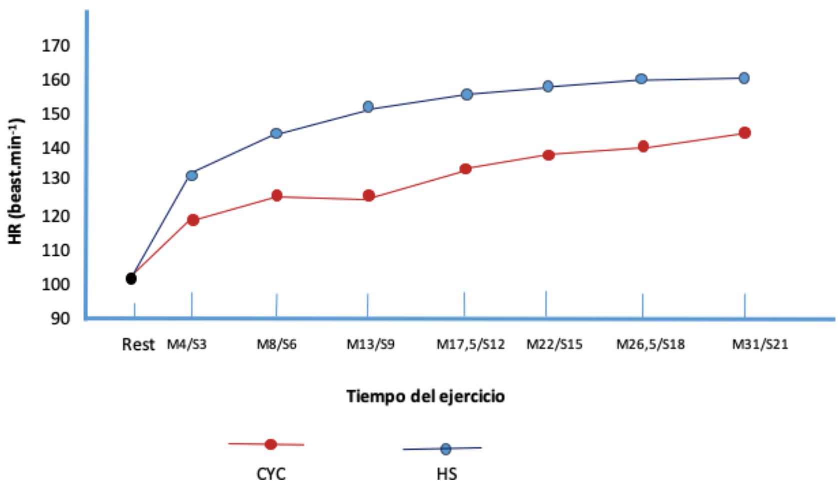

Figura 5. Respuesta de la FC durante pruebas de carga constante realizadas a una carga de trabajo de LT. Comparación entre cicloergómetro (línea roja) i Media sentadilla (línea azul). Adaptado de Garnacho-Castaño et al. (10).

Respecto al comportamiento del VO_2, éste aumenta significativamente en los primeros cuatro minutos del ejercicio, para mantenerse con valores estables a partir del cuarto minuto hasta la finalización del ejercicio (Figura 6) (10).

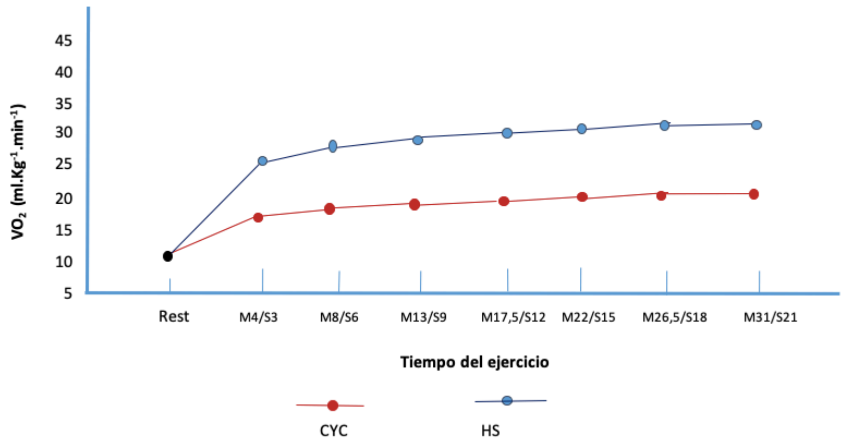

Figura 6. Respuesta del VO_2 durante pruebas de carga constante realizadas a una carga de trabajo de LT. Comparación entre cicloergómetro (línea roja) y Media sentadilla (línea azul). Adaptado de Garnacho-Castaño et al. (10).

En referencia a la VE, cuando se inicia el ejercicio se produce un aumento, de hecho, al igual que la respuesta de la FC, se puede observar un aumento significativo de la respiración antes del inicio del ejercicio como respuesta anticipatoria. A medida que aumenta la intensidad se alcanza un punto determinado en el cual la ventilación aumenta de manera desproporcionada en relación con el incremento de consumo de O_2. Este punto se denomina umbral ventilatorio y en general se produce cuando se alcanza el 55-70% del VO_{2max} (55). A partir de este punto, la VE se mantiene en valores estables hasta la finalización del ejercicio (10).

Las respuestas cardiorrespiratorias agudas al ejercicio dependen de la intensidad y la duración del ejercicio, y también de las diferentes modalidades del ejercicio (por ejemplo, cinta de correr, cicloergómetro, elíptica y remo) (57). Hay varias características inherentes a cada modalidad de ejercicio (el peso, la posición del cuerpo, la utilización de la masa muscular, el movimiento del cuerpo superior y/o inferior) que, junto con sujetos específicos (por ejemplo, niveles de actividad física, experiencia, etc.) y la demanda del ejercicio (intensidad, duración) influyen en las respuestas fisiológicas agudas (5,6,58).

2.4.2.3 El componente lento del consumo de oxígeno

La respuesta de la cinética del VO_2 al ejercicio depende de la intensidad de éste. Se sabe que el VO_2 tiende a aumentar lentamente durante cualquier prueba de ejercicio de tasa de trabajo constante que involucre acidosis láctica sostenida, superando el componente primario iniciado al inicio del ejercicio. Esta respuesta de VO_2, conocida como "Componente lento de VO_2" (VO_{2SC}), se define como el aumento continuo de VO_2 más allá del tercer minuto de ejercicio (59), hasta que se alcanza un estado estacionario retrasado o se alcanza el VO_2 máximo (60). Durante el ejercicio de carga constante a largo plazo, la cinética del VO_2 aumenta el gasto de energía por encima de lo que se predice a partir de la relación de la tasa de trabajo submáxima del VO_2, lo que conduce a una eficiencia de trabajo reducida y fatiga prematura (Figura 7). Por lo tanto, un VO_{2SC} limitado podría ser un parámetro importante para determinar el rendimiento de resistencia (59).

Como sugieren algunos autores, el VO_{2sc} podría verse afectado por el comportamiento de varios parámetros como la carga de potencia, el VO_2, el LT, el acondicionamiento de rendimiento y la eficiencia cardiorrespiratoria (61).

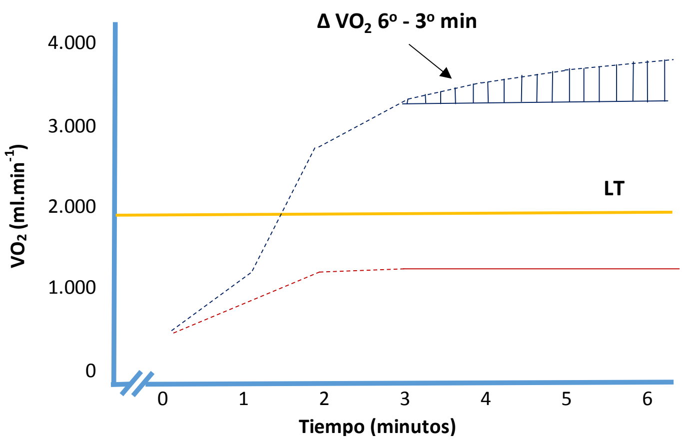

Figura 7 Consumo de oxígeno durante un ejercicio de carga constante por debajo (línea inferior) y por encima (línea superior) del umbral láctico. Obsérvese lo cinético del componente lento del consumo de oxígeno, expresado como la diferencia entre el tercer y sexto minuto del ejercicio, durante el ejercicio realizado o intensidad superior al umbral láctico.

La potencia de salida desarrollada en el LT determinará la amplitud de la respuesta VO_{2sc}. Por tanto, la intensidad LT juega un papel clave en la evaluación de VO_{2sc}. Según el modelo de tres fases (30), dos LT (LT_1 y LT_2) son reconocidos durante la prueba de ejercicio cardiopulmonar (47). LT_1 se considera como "umbral aeróbico" en 40-60% de VO_{2max} (ejercicio ligero), y LT_2 se distingue como "umbral anaeróbico" al 60–90% de VO_{2max} (ejercicio moderado a intenso). Obviamente, el VO_{2sc} a intensidad LT_2 aumentará a una mayor extensión que a la intensidad LT_1 durante el ejercicio de carga constante. La magnitud de VO_{2sc} se ha correlacionado con el porcentaje (62) y el reclutamiento de fibras musculares tipo II (63). En este sentido, el VO_{2sc} revela un reclutamiento gradual de las fibras tipo II en relación a la duración del ejercicio (64,65), mientras que las fibras tipo II son menos eficientes que las fibras tipo I.

2.4.2.4 La economía y la eficiencia

La eficiencia mecánica bruta (GME), o simplemente la eficiencia, se define como la proporción del trabajo mecánico realizado respecto de la energía global invertida. Es decir, qué fracción de energía química utilizada se convierte en trabajo mecánico. La GME es un determinante clave del rendimiento en ejercicios de resistencia (66).

*Eficiencia (%) = 100 * Trabajo Mecánico / Energía Química*

La GME se calcula como el cociente entre el trabajo realizado por minuto (i.e., vatios convertidos a kcal/min) y la energía gastada por minuto (kcal/min) (67). El gasto energético por minuto (kcal/min) puede calcularse a partir del VO_2 y el RER, usando las tablas de Lusk (68) o las de Peronnet y Massicotte (69).

El cambio en la GME, que estima los efectos de la alcalinización de la sangre sobre las pérdidas de la eficiencia muscular, es un factor determinante en el VO_{2SC} (59).

Ha sido reportado que la eficiencia mecánica total está relacionada con la proporción de fibras musculares de tipo I (70). Horowitz et al. (71) mostraron que cuando un grupo de ciclistas de competición fue dividido de acuerdo a la proporción de fibras tipo I (alta=73%, normal=48%), el subgrupo que tuvo mayor proporción de fibras tipo I produjo una potencia significativamente más alta para un VO_2 dado durante una evaluación de 1 hora, indicando una mayor eficiencia. Por tanto, los deportistas con una proliferación mayor de fibras intermedias o rápidas (tipo II), probablemente desarrollen una menor eficiencia en esfuerzos prolongados ante una misma intensidad de carga.

Otro de los factores que afectan al rendimiento de la resistencia y que está estrechamente vinculado con la eficiencia mecánica es la economía. La economía metabólica muscular es entendida como la producción de trabajo relativa a la captación de oxígeno o EE durante un ejercicio de resistencia (72). Es usual evaluar la economía en los ejercicios de resistencia, demostrándose que la economía en la carrera y el ciclismo está relacionada con el rendimiento de la resistencia (73,74) y que esta economía puede variar considerablemente incluso en un grupo de individuos altamente capacitados (75–77). Al igual que ocurría en el VO_{2sc} y la eficiencia, existe una importante relación entre la economía y el tipo de fibras implicadas en las modalidades consideradas de resistencia.

En un estudio de Hunter et al. (72), se muestra por primera vez que la relación inversa entre la economía metabólica muscular y la capacidad oxidativa está presente a nivel del tejido muscular, al menos para el ejercicio de flexión plantar isométrica. Lo que lleva a concluir que la relación inversa entre la economía del ejercicio y la capacidad oxidativa está mediada, al menos parcialmente, por la distribución del tipo de fibra, es decir, las fibras de Tipo IIa son menos eficientes y económicas y, por lo tanto, tienen una mayor demanda de energía y oxígeno (72).

De lo expuesto anteriormente, se deduce que las fibras con menos capacidad oxidativa condicionarán el rendimiento en las modalidades deportivas de resistencia, provocando la aparición prematura de la fatiga mecánica (14).

2.4.3 La eficiencia ventilatoria

Durante el CPET, el aumento VE y la eliminación del VCO_2 es esencial para el control homeostático del pH de todo el cuerpo (72). La relación existente entre la VE y el VCO_2 determina la eficiencia ventilatoria durante el ejercicio.

La VE se estima por medio del Volumen Minuto Respiratorio (VMR), equivalente al volumen total de aire respirado de forma espontánea, sin forzar voluntariamente la amplitud de la respiración, en un minuto de tiempo. Corresponde al producto volumen corriente (VC), por la frecuencia respiratoria (FR).

Se expresa en $l \cdot min^{-1}$

$$VMR = VE\ (L) \times FR\ (ciclos \cdot min^{-1}) = (l \cdot min^{-1})$$

Hay cuatro formas comunes para medir la eficiencia ventilatoria durante una prueba incremental:

- Utilizando la pendiente de la relación entre el VCO_2 y la VE (pendiente VE/VCO_2) (78).

- El equivalente más bajo de CO_2 durante el prueba incremental ($LEqCO_2$) (79).
- El equivalente de CO_2 en el segundo umbral ventilatorio ($EqCO_2VT_2$) (79).
- La pendiente de la eficiencia de la absorción de oxígeno (OUES) (80).

En general, un equivalente más bajo de CO_2 indica una mayor eficiencia ventilatoria (79). Los OUES representan la tasa de aumento del VO_2 en respuesta a una VE dado durante el ejercicio incremental, lo que indica la eficacia con la que se extrae el oxígeno y se ingresa en el cuerpo (81).

La eficiencia ventilatoria se estudia generalmente en el rendimiento deportivo (82), en sujetos sanos (83), y principalmente en diferentes enfermedades o patologías (84–86), estableciendo la pendiente de la relación lineal entre la VE y el VCO_2 (VE/VCO_2 *slope*; terminología utilizada en inglés) durante una prueba incremental hasta el umbral anaeróbico (87) o el umbral ventilatorio (81) o el punto de compensación ventilatoria (88) en los ejercicios de resistencia. Otra opción común es el OUES mediante un modelo lineal alternativo (VO_2 = log10 VE + b). El OUES indica la eficiencia con la que se extrae el O_2 y se introduce en el cuerpo durante el ejercicio incremental (81).

Es común evaluar la eficiencia de la ventilación durante las pruebas incrementales. Sin embargo, se pueden recomendar pruebas de carga constante prolongada a intensidad ligera y moderada como una buena opción en el entorno de la salud clínica para determinar la pendiente del VE/VCO_2 (89) o el OUES. Esto es porque se somete al paciente a una prueba de esfuerzo incremental extenuante y, por ende, el estrés cardiorrespiratorio durante la prueba es mucho menor.

2.5 Los ejercicios con resistencias

Son los denominados en el ámbito científico como "*resistance exercises*" o conocidos popularmente como ejercicios de fuerza. Son un tipo de ejercicio físico que se caracteriza por el uso de la resistencia externa para inducir la contracción muscular, lo que favorece la fuerza, la resistencia anaeróbica y el tamaño de las fibras musculares esqueléticas. Un ejemplo de estos ejercicios serían el press de banca, la sentadilla, pullover, etc. En resumen, cualquier ejercicio que se pueda realizar en un gimnasio.

2.5.1 El ejercicio de carga incremental

Respecto a la existencia de protocolos de ejercicio incremental con resistencias en las extremidades inferiores, existen 4: uno de ellos desarrollado por nuestro grupo de investigación en 2015 que es el que ha sido utilizado en los estudios que comprenden esta tesis (90). A parte de éste, existen 3 protocolos previos: el desarrollado por Villagra et al. (91), el de Simões et al. (92) y el desarrollado por de Sousa et al. (56).

Por un lado, Villagra et al. (91) establecieron un protocolo de sentadilla consistente en realizar una flexión de rodilla entre 45° y 50° al ritmo de un metrónomo a un ritmo de 120 $b \cdot m^{-1}$. La secuencia de movimiento ocupó 5 tiempos. En el protocolo de rebote, el sujeto se puso en cuclillas en el tiempo 1, apareció en el tiempo 2 y luego descansó en los tiempos 3, 4 y 5. En el protocolo de no rebote, los sujetos se pusieron en cuclillas en el tiempo 1, descansaron en la posición en cuclillas para los tiempos 2 y 3, subieron al ritmo 4 y descansaron en la posición de pie en el ritmo 5. Hubo, por lo tanto, 24 flexiones de rodilla en 120 $b \cdot m^{-1}$ y 96 flexiones en 4 series en ambos protocolos. Después de un descanso de 5 minutos, se repitió el procedimiento con los sujetos vistiendo una chaqueta lastrada que contenía primero el 5%, luego el 10% y finalmente el 15% de la masa corporal.

Por otro lado, Simões et al. (92) establecieron un protocolo incremental de prensa de piernas, que se inició con una carga del 10% 1RM, con aumentos posteriores del 10% hasta alcanzar una carga del 30%. Posteriormente, el ajuste de carga incremental se redujo al 5% de la 1RM hasta el agotamiento, con el objetivo de aumentar el número de series y permitir una mejor visualización de los ajustes fisiológicos al aumentar la carga. En cada porcentaje de esfuerzo, el voluntario realizó 4 minutos de ejercicio a un ritmo de movimiento de 12 repeticiones por minuto, manteniendo la cadencia respiratoria con cada repetición realizada en 5 segundos (2 segundos de duración para la extensión y 3 segundos de flexión de rodilla y cadera), con el ritmo controlado por órdenes verbales. Al final de los 4 minutos del ejercicio, un período de recuperación de 15 minutos seguidos (92) .

Y por último, de Sousa et al. (56) utilizaron un protocolo similar al anterior en el ejercicio de la prensa de piernas. Realizaron un test incremental a diferentes intensidades relativas (% 1RM). Las intensidades seleccionadas durante la prueba incremental del ejercicio de prensa de piernas fueron 10%, 20%, 25%, 30%, 35% y 40% de 1RM. El objetivo de este test fue determinar el punto de inflexión (LT) a partir del cual las bLa en sangre comenzaban a incrementar desproporcionadamente. Esta división de intensidades se eligió debido a estudios previos que demostraron que la intensidad del LT en los ejercicios con resistencias era de alrededor del 30% de 1RM (93,94). Cada serie a la intensidad relativa correspondiente duró 1 minuto. Los sujetos realizaron 20 repeticiones y cada repetición duró aproximadamente 3 segundos. Durante una recuperación pasiva de 2 minutos entre series, se aumentó la intensidad (% 1RM) y se extrajo la muestra de sangre para determinar las bLa. El final de la prueba se determinó ya fuera por la incapacidad del sujeto para realizar el movimiento dentro de la técnica correcta establecida previamente o por la incapacidad para realizar el número de repeticiones establecidas para cada serie (56).

2.5.1.1 El umbral láctico

Varios estudios se han centrado en las pruebas de ejercicios con resistencias incrementales (10,56), diseñados para identificar el punto de transición entre el metabolismo aeróbico y anaeróbico, reconocido como el LT (67), que se define como la intensidad de la carga durante el ejercicio incremental en el que las concentraciones de lactato en sangre aumentan exponencialmente (95). Esta se considera la intensidad de carga que respalda la prescripción del entrenamiento de resistencia y la monitorización del progreso del entrenamiento para la población sana, los atletas y pacientes que están en procesos de rehabilitación (95).

El LT se puede detectar utilizando dos métodos diferentes según Moreira et al. (2008); Simões et al. (2010) y de Sousa et al. (2011) (92,94,96). El LT se puede establecer con el método de inspección visual y el método de ajuste del algoritmo.

El primer procedimiento consiste en detectar visualmente el inicio del aumento exponencial en una gráfica de la bLa contra la carga de trabajo (21). Usando este método, dos observadores experimentados determinan de forma independiente el LT en cada sujeto. Cuando hay desacuerdo entre los observadores, se busca la opinión de un tercer observador.

El LT se establece también utilizando el método de ajuste algorítmico descrito por de Sousa et al. (2011) (96) basado en el procedimiento descrito por Orr et al. (97), como la intensidad de trabajo en la que las bLa comienzan a aumentar de manera exponencial (98). El LT se localiza mediante regresión lineal de 2 segmentos computarizada fijando las 2 ecuaciones de regresión lineal que emergen para cada segmento en el punto de intersección entre una gráfica de la bLa en sangre y la intensidad relativa.

2.5.1.2 Repuestas cardiorrespiratorias agudas

Las respuestas cardiorrespiratorias agudas no han sido determinadas en los ejercicios incrementales con resistencias hasta la extenuación, a diferencia de los ejercicios de resistencia. Sin embargo, sí que fueron establecidas en los ejercicios incrementales con resistencias hasta el umbral láctico (10,56).

Respecto a las respuestas cardiovasculares durante los ejercicios con resistencias, la presión sanguínea sistólica (SBP) y la FC aumentan significativamente, mientras que los índices de variabilidad del ritmo cardíaco (HRV) disminuyen en la carga máxima de ejercicio en comparación con los valores en reposo, lo que respalda la afirmación de que los ejercicios con resistencias provocan modificaciones hemodinámicas, posiblemente debido a las alteraciones en el flujo sanguíneo (99). Con respecto a la prensa de piernas, Simões et al. identificaron el porcentaje de 1RM donde estas alteraciones cardiovasculares se hicieron prominentes (92).

Los valores medios de la FC una intensidad de LT son mayores en los ejercicios con resistencias que en los ejercicios de resistencia. La elevada respuesta de la FC puede tener su origen en la participación de una masa muscular activa más grande durante el ejercicio de la HS en los diferentes patrones de reclutamiento neuromuscular en ambas modalidades de entrenamiento (100). Así mismo, se ha comprobado que las concentraciones de lactato en sangre a intensidad LT son estadísticamente mayores en ejercicios con resistencias en comparación con ejercicios de resistencia (100).

2.5.2 El ejercicio de carga constante

Con respecto a los protocolos de carga constante en los ejercicios con resistencias, tampoco se han desarrollado suficientes tipos de protocolos. Los estudios previos a esta tesis que comparan los ejercicios de resistencia con los ejercicios con resistencias son limitados, por lo que solo hemos encontrado un protocolo previo diferente al aplicado por nuestro grupo de investigación en ejercicios aplicados a las extremidades inferiores; el desarrollado por de Sousa et al. con la prueba de la prensa de piernas (56). Este ejercicio con resistencias a carga constante se realizó con una carga de trabajo correspondiente a la intensidad del LT. En dicho protocolo, los sujetos realizaron 30 minutos de ejercicios de resistencia muscular divididos en 15 series. Cada serie duró 1 minuto y los sujetos realizaron 20 repeticiones. Cada repetición duró aproximadamente 3 segundos, controladas por comandos visuales y verbales. La recuperación pasiva entre series duró 1 min.

Para determinar las bLa, las muestras de sangre (25 µl) se recogieron en reposo y 30 segundos después del final de la serie (S) 3 (S3), S6, S9, S12 y S15. Durante el ejercicio con resistencias a carga constante, VE, VO_2 y VCO_2 se midieron de forma continua.

El estudio muestra que, en intensidad baja a moderada, el ejercicio puede mantenerse a lo largo del tiempo sin una acumulación continua de bLa, lo que refleja un metabolismo predominantemente aeróbico. Además, después de un aumento inicial en la concentración de bLa, esta variable mostró un comportamiento estable al final del ejercicio.

El comportamiento de la FC durante el ejercicio con resistencias de carga constante mostró un aumento inicial, seguido de una estabilización hasta el final del ejercicio, lo que indica un estado cardiovascular constante en la intensidad del umbral anaeróbico.

El VO_2 y el VCO_2 tuvieron un comportamiento similar durante el ejercicio con resistencia de carga constante, aumentando de reposo a S3 de manera exponencial y luego de manera suave y progresiva hasta el final del ejercicio.

En definitiva, estos parámetros se estabilizan durante el ejercicio con resistencias de carga constante a intensidad LT.

A pesar de disponer de éste como único protocolo en nuestros estudios, no se pudo utilizar, ya que, aunque el ejercicio era de características similares (ejercicio con resistencias de carga constante a LT) no se conseguían los resultados esperados, por el nivel de fatiga. Este hecho nos llevó a desarrollar un nuevo protocolo para determinar el LT, ya que los ejercicios empleados de carga constante (HS) en nuestros estudios no nos permitían establecerlo con los ejercicios de prensa de piernas que utiliza en sus estudios de Sousa et al. ya que las demandas metabólicas y ventilatorias no son equiparables en dichos ejercicios.

2.5.2.1 El comportamiento del lactato

Respecto a este parámetro tampoco se dispone de evidencia científica previa. Se conoce que durante las pruebas de ejercicios con resistencias de carga constante prolongada a una intensidad de carga equivalente al LT, se observa una estabilización en los niveles de lactato sanguíneo y en la respuesta cardiorrespiratoria en ejercicios de prensa de piernas (56) y en HS (8), como también ocurre en ejercicios de resistencia (10).

Se ha demostrado que tanto en los ejercicios a carga constante a LT de resistencia como en los ejercicios a carga constante a LT con resistencias, el comportamiento del lactato es estable en ambos (7).

2.5.2.2 Las respuestas cardiorrespiratorias

Durante el ejercicio de resistencia a carga constante, existe una estabilización de bLa (101). En intensidades bajas y moderadas, el ejercicio puede mantenerse a lo largo del tiempo sin una acumulación continua de bLa, en el que se produce un equilibrio entre la tasa de aparición de lactato y su desaparición de la sangre (24,102).

El comportamiento de la FC durante el ejercicio con resistencia con carga constante muestra un aumento inicial, seguido de una estabilización hasta el final del ejercicio, lo que indica un estado cardiovascular constante en una intensidad del LT. El aumento inicial de la FC en los ejercicios con resistencias de carga constante, está modulado por el sistema nervioso autónomo, que promueve una retirada de la actividad parasimpática y un aumento de la actividad simpática en el corazón (99,103). Además, la actividad simpática también afecta la vascularización, promoviendo la redistribución del flujo sanguíneo y la capacidad venosa reducida. Estos ajustes fisiológicos son favorables para el aumento del gasto cardíaco, necesario para ajustar la demanda metabólica en los músculos activos durante el ejercicio (101).

En el estudio de Sousa et al. (101), la salida de oxígeno y el VCO_2 aumentan desde el reposo hasta el tercer minuto y luego alcanzan un estado estable hasta el final del ejercicio de carga constante.

Los parámetros ventilatorios están estrechamente relacionados con los parámetros metabólicos, ya que el aumento de los productos metabólicos liberados por los músculos activos estimula los quimiorreceptores periféricos y centrales, que a su vez desencadenan el aumento de las respuestas respiratorias reflejas (104).

Las respuestas respiratorias (VO_2, VCO_2, VE, RER), en los ejercicios con resistencias de carga constante, muestran un estado estable. Hay un aumento de estos parámetros desde el inicio del ejercicio hasta el minuto 4 (S3), y después aumentan de forma suave y continua hasta al final. Sin embargo, las respuesta ventilatorias (excepto RER) son significativamente mayores para los ejercicios de resistencia "*endurance exercises*" en cicloergómetro (CYC) respecto a los ejercicios con resistencias "*resistance exercises*" (HS) (10).

2.6 La fatiga mecánica

El término fatiga se utiliza generalmente para describir la reducción en el rendimiento muscular durante un esfuerzo continuo que está acompañado por una sensación de cansancio generalizado (25). Otra definición alternativa es la incapacidad de mantener la potencia necesaria para continuar el trabajo muscular a una intensidad dada (25).

Para distinguir la fatiga de la debilidad o del daño muscular, se puede pensar en la fatiga como un estado que puede revertirse mediante el reposo.

La fatiga puede producirse por:

- Reducción de la tasa de producción de energía (ATP-CPr, glucólisis anaeróbica y oxidación)
- Acumulación de subproductos metabólicos como el lactato y el (H^+)
- Fallos en los mecanismos contráctiles de la fibra muscular
- Alteraciones en el sistema nervioso

La fatiga mecánica en las extremidades inferiores se puede evaluar mediante una prueba de *CounterMovement Jump* (CMJ) (105).

Hasta ahora, se han descrito 2 componentes esenciales de los modelos de fatiga: la fatiga inducida y la cuantificación de la fatiga (106). En este estudio, la fatiga se evaluó en términos de pérdidas de potencia y altura producidas en el CMJ. Otros autores también han utilizado mediciones de altura de salto vertical antes y después de la prueba para determinar el grado de fatiga producida (107,108).

3. JUSTIFICACIÓN. PLANTEAMIENTO DEL PROBLEMA

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El test de ejercicio cardiopulmonar es una práctica muy usual en la evaluación clínica y del rendimiento en los ejercicios de resistencia en condiciones de laboratorio. Este tipo de valoraciones han sido usualmente realizadas tanto en test incrementales, como en pruebas constantes en ejercicios como el tapiz rodante y el cicloergómetro. Sin embargo, no es un tipo de evaluación habitual en los ejercicios con resistencias. Quizás porque este tipo de ejercicios son de naturaleza anaeróbica y, por tanto, la gestión de los tiempos de recuperación es muy diferente a las pruebas continuas en los ejercicios de resistencia, como por ejemplo el cicloergómetro.

Recientemente, nuestro grupo de investigación (10) se ha aventurado a adentrarse en el análisis de las respuestas cardiorrespiratorias en los ejercicios con resistencias (HS), en un metabolismo predominantemente aeróbico a intensidad de LT. Los principales hallazgos fueron que las variables cardioventilatorias y las bLa en sangre se mantuvieron estables en el ejercicio de la HS, a pesar de que en el cicloergómetro se observó un incremento en la respuesta cardiorrespiratoria. Sin embargo, solo el ejercicio de la HS indujo fatiga mecánica. Dado que las respuestas cardiorrespiratorias fueron estables en ambos ejercicios, manteniendo constantes y en valores bajos las bLa en sangre, es asumible que la fatiga en la HS podría venir asociada en mayor medida a factores mecánicos que al estrés cardiorrespiratorio y metabólico generado (10). Asociada a esta fatiga mecánica, podría ser esperado un descenso más acusado de la eficiencia mecánica. En esta misma línea de especulación, esta disminución de la eficiencia mecánica podría estar relacionada con un incremento del VO_{2sc} (59).

Las pruebas de ejercicios de resistencia, con frecuencia se centran en el VO_{2max} el LT y la eficiencia mecánica, junto con el tiempo necesario para completar la prueba en la evaluación cardiorrespiratoria y del rendimiento metabólico en condiciones de laboratorio (109,110). El comportamiento de estos parámetros (VO_2, LT, potencia), podrían alterar el carácter de la cinética del VO_2 (VO_{2sc}) y la eficiencia respiratoria durante el ejercicio (61). Además la bibliografía científica indica también varios factores fisiológicos que, individual o conjuntamente podrían también influir en el comportamiento del VO_{2sc}, incluido el tipo de fibra muscular (111), el tipo de acción y contracción muscular (65), el reclutamiento de unidades motoras y el tipo de ejercicio (112). Se ha reportado que el VO_{2sc} es más bajo en la carrera que en ejercicios de ciclismo (112,113), y más alto en ejercicios de ergómetro de brazo, que el de pierna (114), lo que indica que el VO_{2sc} es dependiente del ejercicio. Esta diferencia entre los modos de ejercicio se asocia principalmente con la amplitud de la respuesta (112) que a su vez está condicionada por la intensidad de carga durante la prueba de carga constante (115) Por lo tanto, el VO_{2sc} es dependiente del ejercicio y la intensidad. Esta respuesta en la cinética del VO_2 podrían condicionar la eficiencia mecánica durante la prueba, incrementando la fatiga muscular.

El análisis del VO_{2sc} y de la eficiencia mecánica es usualmente evaluada en los ejercicios de resistencia, sin embargo, hay una importante carencia de información en los ejercicios con resistencias en un protocolo constante a intensidad de LT.

Por otro lado, el fitness cardiorrespiratorio es habitualmente evaluado mediante la eficiencia ventilatoria en los ejercicios de resistencia, concretamente mediante la pendiente del VE/VCO_2 y el OUES. Muchos estudios han evaluado la pendiente del VE/VCO_2 y el OUES por edad, sexo, nivel de fitness y en la clínica en los ejercicios de resistencia (81, 82, 83, 85). No es habitual valorarla comparándola entre diferentes modalidades deportivas. Esta incertidumbre incrementa con respecto a los ejercicios con resistencias, ya que la eficiencia ventilatoria no ha sido evaluada ni comparada con los ejercicios de resistencia.

Es por eso por lo que los tres artículos de esta tesis pretenden dar respuesta a tres interrogantes de los cuales no hay evidencia científica.

Por un lado, cómo se comporta el VO_{2sc}, la EE y GME en ejercicios con resistencias de carga constante a intensidad de LT. Por otro lado, también es importante conocer la economía, la eficiencia mecánica y la fatiga de los ejercicios con resistencias de carga constante a intensidad de LT. Y por último se hace imprescindible determinar la eficiencia ventilatoria en los ejercicios con resistencias de carga constante a intensidad LT y comparar ésta eficiencia ventilatoria a través de la pendiente del VE/VCO_2 y el OUES tanto entre ambas pendientes y entre diferentes modalidades de ejercicio, para ver si podrían ser más eficientes los ejercicios con resistencias que los ejercicios de resistencia a la misma intensidad de carga, tanto en el rendimiento deportivo como en programas de ejercicios relacionados con la salud en poblaciones diversas (por ejemplo, adultos sanos, estilo de vida sedentario, personas mayores, deportistas, enfermedades, etc.).

4. OBJETIVOS

4. OBJETIVOS

A continuación, se describen los objetivos que se pretenden alcanzar y las hipótesis que se pretenden demostrar correspondientes a cada uno de los objetivos específicos desarrollados en cada artículo.

Objetivo general

Comparar las respuestas cardiorrespiratorias y metabólicas, el VO_{2sc}, la eficiencia mecánica y ventilatoria, y la fatiga mecánica entre el cicloergómetro (CYC) (*endurance exercise*) y la HS (*resistance exercise*) durante una prueba de carga constante a intensidad del LT.

Objetivos específicos

OE1. Evaluar el comportamiento del VO_{2sc}, la EE y la GME durante un test de HS a una carga constante a intensidad del LT, determinando la fatiga mecánica inducida al final de la prueba (artículo 1).

OE2. Comparar el $VO2_{sc}$, la eficiencia y/o economía, las respuestas metabólicas y la fatiga mecánica entre el cicloergómetro y el ejercicio de HS durante una prueba de carga constante a una intensidad correspondiente al LT (artículo 2).

OE3. Comparar las respuestas cardiorrespiratorias y la eficiencia ventilatoria, medida mediante el OUES y la pendiente del VE/VCO_2, entre el ejercicio de HS y del cicloergómetro en una prueba a carga constante a intensidad del LT (artículo 3).

OE4. Determinar la relación existente entre el OUES y la pendiente del VE/VCO_2 en los ejercicios de la HS y el cicloergómetro (artículo 3).

5. HIPÓTESIS

5. HIPÓTESIS

Se han desarrollado tres hipótesis de trabajo de acuerdo con la formulación de los objetivos específicos establecidos en las publicaciones presentadas.

i. En el ejercicio de la HS, el VO_{2sc} y el gasto de energía incrementan lenta y progresivamente mientras la eficiencia disminuye paulatinamente durante un test a carga constante a intensidad del LT, consecuentemente incrementando la fatiga mecánica al final del test (OE1).

ii. En el ejercicio de la HS, el VO_{2sc} y el gasto de energía aumenta ligera y progresivamente, mientras la eficiencia mecánica disminuye en mayor medida que en el ejercicio del cicloergómetro, durante un test a carga constante a intensidad del LT, razonablemente la fatiga mecánica será afectada especialmente al final del test en el ejercicio de la HS (OE2).

iii. Los ejercicios de resistencia como el cicloergómetro son usualmente empleados para el desarrollo del fitness cardiorrespiratorio, mientras que los ejercicios con resistencias como la HS son utilizados para el desarrollo de la fuerza y la resistencia muscular. Por tanto, es plausible afirmar una mayor eficiencia ventilatoria medida mediante la pendiente del VE/VCO_2 y el OUES en el ejercicio del cicloergómetro (OE3).

    a. Los sujetos que presentan una mayor eficiencia ventilatoria cuantificada a través de la pendiente del VE/VCO_2 poseen un mayor OUES (OE4).

    b. Los participantes que adquieren una mayor eficiencia ventilatoria en el ejercicio de la HS tienen una mayor eficiencia ventilatoria en el cicloergómetro (OE4).

6. INFORME DE LOS DIRECTORES

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TecnoCampus
Escola Superior
de Ciències de la Salut

Centre adscrit a:
upf. Universitat Pompeu Fabra Barcelona

En Barcelona, a 27 de mayo de 2019

La Dra. Noemí Serra Payá y el Dr. Manuel Vicente Garnacho Castaño declaran, como directores de la tesis doctoral presentada por el doctorando Lluís Albesa Albiol titulada "Evaluación del componente lento del consumo de oxígeno de la eficiencia ventilatoria y mecánica en los ejercicios con resistencias", la autenticidad del factor de impacto de los artículos *Journal Citation Reports* presentados, así como la implicación y dedicación del doctorando en la elaboración de dichos artículos científicos que conforman esta tesis doctoral.

Lluís Albesa ha participado consecuentemente en la elaboración de los artículos, como queda reflejada en la relación de autores de todos los artículos, figurando como primer autor en uno de ellos. Además, ha participado activamente en los experimentos que conducen a la obtención y el análisis de los datos.

A continuación, detallamos la relación de artículos que conforman esta tesis:

Artículo I:

Título: **Oxygen uptake slow component and the efficiency of resistance exercises**.

Autores: Garnacho-Castaño MV, **Albesa-Albiol L**, Serra-Paya N, Gomis M, Pleguezuelos Cobo E, Guirao-Cano L, Guodemar-Pérez J, Carbonell T, Domínguez R, Maté-Muñoz JL.

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Artículo II:

Título: **The slow component of oxygen uptake and efficiency in resistance exercises: A comparison with endurance exercises.**

Autores: Garnacho-Castaño MV, **Albesa-Albiol L**, Serra-Payá N, Gomis Bataller M, Felíu-Ruano R, Guirao Cano L, Pleguezuelos Cobo E, Maté-Muñoz, JL**.**

Revista: Frontiers in Physiology.

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Artículo III:

Título: **Ventilatory efficiency during constant-load test at lactate threshold intensity: Endurance versus resistance exercises.**

Autores: **Albesa-Albiol L**, Serra-Payá N, Garnacho-Castaño MA, Guirao Cano L, Pleguezuelos Cobo E, Maté-Muñoz JL, Garnacho-Castaño MV.

Revista: PloS One.

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Sinceramente,

Dra. Noemí Serra Payá

Dr. Manuel V. Garnacho Castaño

7. ARTÍCULO 1

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Oxygen Uptake Slow Component and the Efficiency of Resistance Exercises

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ABSTRACT

This study aimed to evaluate oxygen uptake slow component (VO_{2sc}) and mechanical economy/efficiency in half squat (HS) exercise during constant-load tests conducted at lactate threshold (LT) intensity. Nineteen healthy young men completed 3 HS exercise tests separated by 48-hour rest periods: 1 repetition maximum (1RM), incremental-load HS test to establish the %1RM corresponding to the LT, and constant-load HS test at the LT. During the last test, cardiorespiratory, lactate, and mechanical responses were monitored. Fatigue in the lower limbs was assessed before and after the constant-load test using a countermovement jump test. A slight and sustained increase of the VO_{2sc} and energy expended (EE) was observed ($p < 0.001$). In blood lactate, no differences were observed between set 3 to set 21 ($p < 0.05$). A slight and sustained decrease of half squat efficiency and gross mechanical efficiency (GME) was detected ($p < 0.001$). Significant inverse correlations were observed between VO_2 and GME (r = 20.93, $p < 0.001$). Inverse correlations were detected between EE and GME (r = 20.94, $p < 0.001$). Significant losses were observed in jump height ability and in mean power output ($p < 0.001$) in response to the constant-load HS test. In conclusion, VO_{2sc} and EE tended to rise slowly during constant-load HS exercise testing. This slight increase was associated with lowered efficiency throughout constant-load test and a decrease in jump capacity after testing. These findings would allow to elucidate the underlying fatigue mechanisms produced by resistance exercises in a constant-load test at LT intensity.

KEY WORDS: gross mechanical efficiency, lactate threshold, mechanical fatigue, energy expended, half squat

INTRODUCTION

Recently, several studies have focused on incremental resistance exercise tests (10,13) designed to identify the point of transition between aerobic and anaerobic metabolism, recognized as the lactate threshold (LT) (3). The LT is defined as the load intensity during incremental exercise at which blood lactate concentrations increase exponentially (39). This is considered the load intensity that supports the prescription of resistance training and monitoring of training progress for the healthy population, athletes, and those undergoing rehabilitation (39).

During prolonged constant-load resistance exercises tests conducted at a load intensity equivalent to the LT, a stabilization is observed in blood lactate levels and in cardiorespiratory response in leg press (10) and half squat (HS) exercise (14), as also occurs in endurance exercises (13). It is known that oxygen uptake (VO_2) tends to slowly rise during any constant work rate exercise test involving sustained lactic acidosis, surpassing the primary component initiated at exercise onset. This VO_2 response, known as the "VO_2 slow component" (VO_{2sc}), is defined as the continued increase in VO_2 beyond the third minute of exercise (12) until a delayed steady state is attained or maximal VO_2 is reached (43). During long-term constant-load exercise, the VO_{2sc} kinetics increases the energy expenditure above that predicted from the submaximal VO_2 work-rate relationship, leading to a reduced work efficiency and premature fatigue. Thus, a limited VO_{2sc} might be an important parameter to determine endurance performance (12).

The scientific literature indicates several physiological factors that individually or jointly could influence on the VO_{2sc} behavior, including muscle fiber type (34), type of muscle action and contraction (35), pattern of motor unit recruitment, and type of exercise (6). It has been reported that the VO_{2sc} is lower in running compared with cycling exercise (6) and higher in arm-crank than leg-cycle exercises (19), indicating that the VO_{2sc} is exercise-dependent.

Although these studies have focused on evaluating the VO_{2sc} in endurance exercises, the VO_{2sc} phenomenon in resistance exercises during a long-term constant-load exercise test has not been explored. It is tempting to suggest that knowledge of VO_{2sc} behavior in resistance exercises might help to elucidate the underlying fatigue mechanisms produced during prolonged constant-load testing. Garnacho-Castaño et al. (14) observed significant losses in height and mean power during the countermovement jump (CMJ) test only in HS exercise (not in cycling) measured at the end of a constant-load exercise test at LT intensity. This decrease in jumping ability after the constant-load HS test could be related to a slow rise in VO_2, and the corresponding increase in energy cost would be associated with progressive fatigue (16). This mechanical fatigue, presumably prompted during a constant-load HS test, would stimulate a preferential glycogen depletion of type I fibers and induce a forced recruitment of type II fibers (21). In addition, a key determinant of the VO_{2sc} is the change in gross mechanical efficiency (GME), which estimates the effects of blood alkalinization on the gradual loss of muscle efficiency (12).

TABLE 1. Descriptive data related to 1RM incremental- and constant-load tests.*

Variables	Mean	*SD*
1RM in HS (kg)	204.9	45.9
Load at LT intensity (kg)	51.0	17.2
LT intensity (%1RM)	25.3	5.0
Lactate in constant test ($mmol\cdot L^{-1}$)	3.3	0.9
$\dot{V}O_2$ at LT intensity ($L\cdot min^{-1}$)	1.6	0.2
$\dot{V}O_2$ at LT intensity ($ml\cdot Kg^{-1}\cdot min^{-1}$)	20.0	2.3
HR at LT intensity ($b\cdot min^{-1}$)	128.6	12.0
RER at LT intensity	0.93	0.0
HSE at LT ($W\cdot L^{-1}\cdot min^{-1}$)	155.7	6.6
GME at LT (%)	44.9	2.0
EE at LT intensity ($Kcal\cdot min^{-1}$)	8.0	0.4

*1RM = 1 repetition maximum; HS = half squat; LT = lactate threshold; $\dot{V}O_2$ = oxygen uptake; HR = heart rate; RER = respiratory exchange ratio; HSE = half squat efficiency; GME = gross mechanical efficiency; EE = energy expended.

Half squat is one of the most popular exercises in resistance training programs. In scientific literature, the VO_{2sc} and economy/efficiency responses to constant-load HS exercise performed at LT intensity are still unknown.

We hypothesized that, as VO_{2sc} increases in a prolonged constant-load test at LT intensity, work efficiency in resistance exercises such as HS should be reduced, and therefore, it would be plausible to propose a causal inverse relationship between the VO_{2sc}, energy expended (EE), and mechanical efficiency. This study aimed to evaluate the VO_{2sc} kinetic, EE, and mechanical efficiency in HS exercise during prolonged constant-load tests conducted at an intensity equivalent to the LT.

METHODS

Experimental Approach to the Problem

Participants performed 3 different tests between 9:00 AM and 15:00 PM (63 hours) each day under the same environmental conditions (temperature: 21–258 C, atmospheric pressure: 715–730 mm Hg, and relative humidity: 40–50%), with a rest period between each test of 48 hours. The test protocols followed the guidelines established by our research group in previous studies (14): (a) 1 repetition maximum (1RM) HS test to determine the % loads to be used in the incremental test, (b) incremental-load HS test to establish the %1RM corresponding to the LT, and (c) constant-load HS test at the LT. In the HS constant-load test, acute cardiorespiratory and metabolic responses were recorded. A Smith machine (Matrix G1-FW161; Madrid, Spain) was used to ensure controlled movements. Mechanical fatigue in the lower limbs was assessed before and after the constant-load tests.

Subjects

The study participants were 19 young, healthy men, all students of the Physical Activity and Sport Sciences (age 21.7 6 1.7 years; height, 180.5 6 5.1 cm; body mass, 81.9 69.5 kg; body mass index, 25.1 6 2.2). Participants had at least 6 months of experience in strength training and all were accustomed to HS exercise. Four exclusion criteria were applied: (a) the use of any medication or performance-enhancing drugs, (b) any cardiovascular, metabolic, neurological, pulmonary, or orthopedic disorders that could limit exercise performance, (c) being an elite athlete, and (d) a 1RM of less than or equal to 150 kg in HS exercise.

Before the study outset, participants were informed of the tests, and written consent was obtained from each subject. The study protocol was approved by the Ethics

Committee of the Alfonso X el Sabio University (Madrid, Spain) and adhered to the tenets of the Declaration of Helsinki.

One Repetition Maximum Half Squat Test. The HS test protocol included a standard warm-up for all subjects, involving 5 minutes of low-intensity running and 5 minutes of joint mobility and dynamic stretching exercises. This was followed by a specific warm-up consisting of 1 set of 3–5 HS repetitions at a relative intensity of 40–60% of the maximum perceived effort. Subjects commenced the 1RM test after a 2-minute rest. This involved 3–5 lifting attempts using increasing weights. The 1RM was defined as the last load lifted by the subject while completing a knee extension to the required position. The rest period between each attempt was 4 minutes.

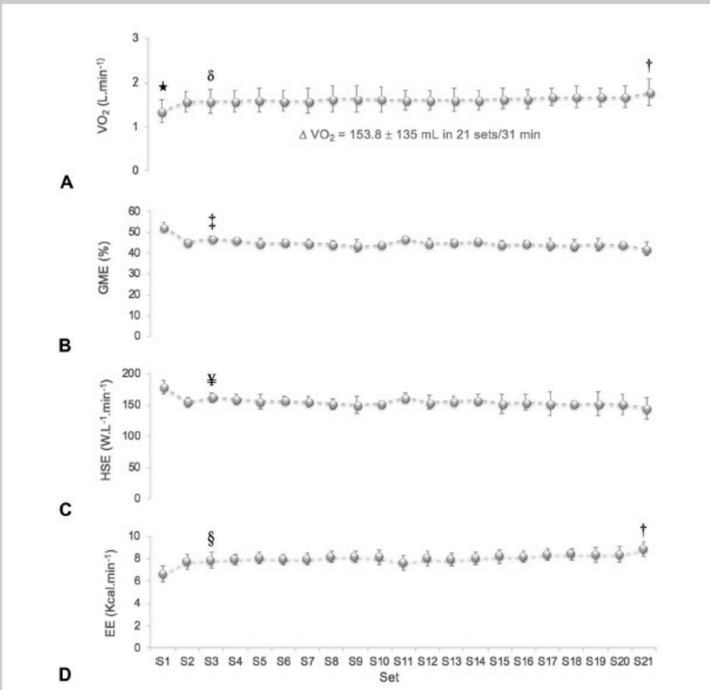

Figure 1. Slow component kinetics (A); gross mechanical efficiency (GME) (B); half squat efficiency (HSE) (C); and energy expended (EE) (D) during constant-load half squat (HS) test at lactate threshold intensity. ★Significant differences vs. checkpoints S3, S6, S9, S12, S15, S18, S21 ($p < 0.001$). δSignificant differences vs. checkpoints S6, S12, S15, S18, S21 ($p < 0.05$). ‡Significant differences vs. checkpoints S6, S9, S12, S15, S18, S21 ($p < 0.05$). ¥Significance differences vs. checkpoints S9, S12, S15, S18, S21 ($p < 0.05$). §Significant differences vs. checkpoints S6, S18, S21 ($p \leq 0.004$). † Significant differences vs. checkpoints S6, S12, S15 ($p < 0.05$).

The HS technique was specified in the protocol. The participants positioned themselves under the barbell in a standing position with the knees and hips fully extended, and legs spread at shoulder width. The barbell was placed on the upper back (trapezius muscle), approximately at the level of the acromion. The subject flexed the knees and hips (eccentric action) to lower the barbell in a controlled manner, until 90° flexion of the knees. From this position, the propulsive (concentric) muscle action was initiated until the knees and hips were fully extended.

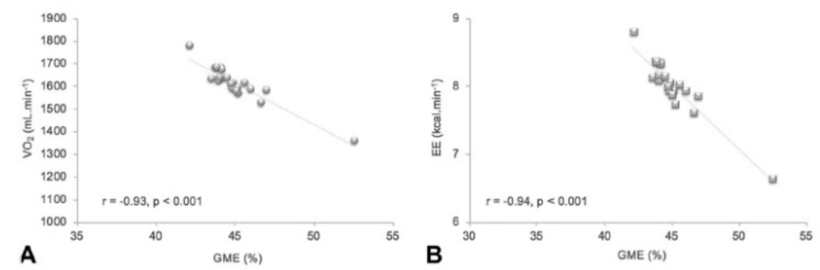

Figure 2. Relationship between (A) $\dot{V}O_2$ and gross mechanical efficiency (GME); (B) energy expended (EE) and GME.

Incremental Half Squat Test. Participants performed the same warm-up as in 1RM HS test. After a 2-minute rest, the incremental HS test was performed in sets at relative intensities of 10, 20, 25, 30, 35, and 40% 1RM as in previous studies (14,27). Each set lasted 1 minute and involved 30 repetitions of 2 seconds each (1 second for the eccentric phase and 1 second for the concentric phase). This rhythm was monitored with a metronome while an observer provided visual and verbal cues. A passive rest of 2 minutes was established between sets while the relative load (%1RM) was increased and blood samples were collected for lactate determination. The test was completed when the subject did not correctly perform repetitions or was unable to continue executing repetitions at the rhythm set for each set at the corresponding relative intensity (%1RM).

Blood samples (5 μL) were obtained by finger pricking 30seconds after the end of each set/relative intensity (10, 20, 25, 30, 35, and 40% of 1RM), and lactate levels determined using a portable lactate analyzer (Lactate Pro LT-1710; Arkray Factory Inc., KDKCorporation, Shiga, Japan). The reliability of this device has been previously evaluated (28). All measurements were rigorously performed by the same expert evaluator.

The LT was established using the algorithm adjustment method based on the procedure described by Orr et al. (31), as the work intensity at which lactate concentrations start to increase in an exponential manner (42). The LT was located through computerized 2-segment linear regression by fixing both linear regression equations emerging for each segment at the point of intersection between a plot of blood lactate concentration and relative intensity. Data treatment was performed using the software package Matlab version 7.4 (MathWorks, Natick, MA, USA).

Constant-Load Half Squat Test at Lactate Threshold Intensity. Participants performed the same warm-up as in 1RM HS test. After 2 minutes, the constant-load HS test was conducted as 21 sets of 15 repetitions of 2 seconds (1 second of concentric exercise and 1 second of eccentric) guided by metronome, visual, and verbal cues. The duration of each set was 30 seconds, with a 1-minute rest period between sets; the complete constant-load test took 31 minutes.

Respiratory exchange data were recorded using a breathby- breath open-circuit gas analyzer (Vmax spectra 29; Sensormedics, Corp., Yorba Linda, CA, USA), which had been previously calibrated. The following variables were monitored: minute ventilation (VE), volume oxygen consumed (VO_2), volume carbon dioxide expired (VCO_2), and respiratory exchange ratio (RER). Heart rate was monitored every 5 seconds by telemetry (RS-800CX; Polar Electro OY, Kempele, Finland).

Blood samples were obtained at rest and 30 seconds after the end of the HS sets (S) S3, S6, S9, S12, S15, S18, and S21, when lactate concentrations were determined as described above for the incremental test. The checkpoints of the lactate samples coincided with the following minutes of testing (M): S3/M4, S6/M8.5, S9/M13, S12/ M17.5, S15/ M22, S18/M26.5, and S21/M31 (test end).

The VO_{2sc} was identified as the difference between VO_2 at the end of exercise and at the end of the third minute of constant-load exercise (ΔVO_2, in $mL \cdot min^{-1}$). The latter was taken as the average VO_2 from 2 minutes 30 seconds to 3 minutes 30 seconds (set 2 to set 3), whereas end exercise values were taken as the average of the last 2 minutes of the tests (29 minutes 0 seconds to 31 minutes 0 seconds/set 20 to set 21).

Mean HS efficiency (HSE) during constant load was expressed in $W \cdot L^{-1} \cdot min^{-1}$, whereas GME was calculated as the ratio of work accomplished per minute (i.e. W in $kcal \cdot min^{-1}$), to energy consumed per minute (i.e. in $Kcal \cdot min_{-1}$) as described elsewhere (8). Energy expenditure was calculated from VO_2 and the RER using the tables of Lusk (25). To determine the GME and HSE, a linear position transducer, Tendo Weightlifting Analyzer System (Trencin, Slovak Republic) was used to measure bar velocity during constant-load HS exercise testing.

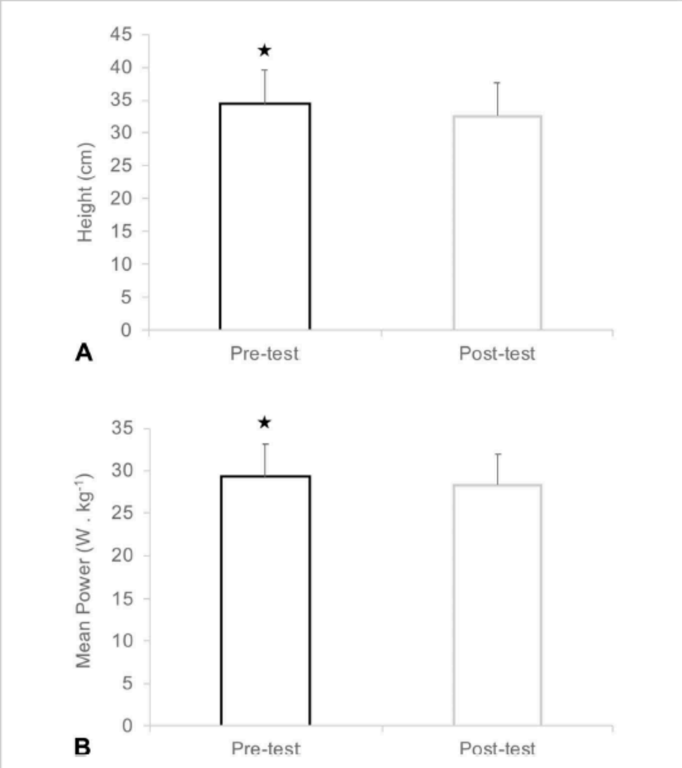

Figure 3. Mechanical fatigue measured as jump height losses (A) and mean power output losses (B) in a countermovement jump test. ★Significant differences vs. post-test ($p < 0.001$).

The reliability and validity of this device has been previously demonstrated (15). The power output was calculated for each repetition based on bar velocity as follows:

- velocity ($m \cdot s^{-1}$) = vertical movement of the bar (m) x time (s^{-1})
- acceleration ($m \cdot s^{-2}$) = vertical bar velocity ($m \cdot s^{-1}$) x time (s^{-1})
- force (N) = system mass (kg) x [vertical acceleration of the bar ($m \cdot s^{-2}$) + acceleration due to gravity ($m \cdot s^{-2}$)]
- power (W) = vertical force (N) X vertical bar velocity ($m \cdot s^{-1}$)

The mean power output was calculated as the average of all repetitions.

Lower Limbs Fatigue. Mechanical fatigue was determined using a CMJ test following a method previously described (14). Briefly, the test was performed using a force plate (Quattro Jump model 9290AD; Kistler Instruments, Winterthur, Switzerland) before and after the constant-load HS test at the LT intensity. Pre-test and post-test jumps were exactly performed before starting the HS test (after warm-up) and after the last blood lactate collection, respectively. Participants performed 3 jumps separated by a rest time of 30 seconds, and the mean values of height and mean power recorded in the 3 jumps were used in the subsequent analyses.

Statistical Analyses

The Shapiro-Wilk test was used to check the normal distribution of data, which are provided as mean ± *SD*. Repeated-measures analysis of variance was used to compare VO_2 kinetics, lactate, EE, GME, and HSE responses. When significant differences emerged, Bonferroni test was used to determine between which checkpoints these occurred. Effect sizes were calculated using partial eta-squared (). Statistical power (SP) and intraclass correlation coefficients were also determined. Pearson product-moment correlation coefficients were calculated to determine a significant relationship between VO_2 and GME, and between EE and GME. To determine mechanical fatigue, student t-test for paired samples was used to evaluate CMJ height and power losses produced in response to the constant-load test at LT intensity. All statistical tests were performed using the software package SPSS Statistics version 23.0 for Mackintosh (SPSS, Chicago, IL, USA). Significance was set at $p < 0.05$.

RESULTS

Descriptive data related to incremental- and constant-load tests are shown in Table 1.

A significant difference in blood lactate levels was observed ($F_{7, 126} = 36.51$, $p < 0.001$, = 0.670, SP = 1), and Bonferroni test confirmed differences between resting and all checkpoints ($p < 0.001$). Although no significant changes ($p < 0.05$) were observed between S3 to S21, a slight rise was detected in the blood lactate kinetics.

The behavior of VO_{2sc} kinetics, GME, HSE, and EE during constant-load HS test at LT intensity is shown in Figure 1. A significant VO_2 increase was detected ($F_{7, 126} = 22.09$, $p < 0.001$, = 0.551, SP = 1), and a slight and sustained increase of the VO_{2sc} was observed (Figure 1A). In GME, a significant slight and sustained decrease was observed throughout the constant-load HS test ($F_{6, 108}$ = 10.06, p < 0.001, = 0.359, SP = 1), and Bonferroni test confirmed changes between S3 and all checkpoints p < 0.05) (Figure 1B). A significant slight and sustained decrease was observed throughout the constant-load test in HSE ($F_{6, 108}$ = 8.56, p < 0.001, = 0.322, SP = 1), and significance differences were found between S3 and S9, S12, S15, S18, S21 checkpoints p < 0.05) (Figure 1C). A significant slight and sustained increases of EE was identified ($F_{6, 108}$ = 10.54, p < 0.001, = 0.369, SP = 1), and Bonferroni test determined significant differences between S21 vs. S3, S6, S12, S15 (p < 0.05) (Figure 1D).

Significant inverse correlations were found between VO_2 and GME (r = -0.93, p < 0.001) (Figure 2A). Significant inverse correlations were detected between EE and GME (r = 20.94, p < 0.001) (Figure 2B).

Intraclass correlation coefficients were 0.964 (confidence F2 interval [95% CI]: 0.932–0.984) for lactate, 0.973 (95% CI: 0.959–0.988) for VO_{2sc}, 0.994 (95% CI: 0.989–0.997) for HSE, and 0.994 (95% CI: 0.990–0.998) for GME.

In response to the constant-load HS test, significant losses were observed in jump height ability (p < 0.001) and in mean power output (p < 0.001) (Figure 3A, B).

DISCUSSION

The principal finding of this study was that VO_{2sc} (small magnitude) and EE tended to rise slowly during constant HS exercise testing conducted at a load intensity equivalent to the LT. In addition, GME and HSE were slightly decreased throughout the HS constant test (Figure 1). Consequently, ΔVO_2 and EE were inversely correlated with GME (Figure 2) because the GME was diminishing as VO_2 and EE were increased throughout the long-term constant-load test.

Although comparable conclusions have been observed in several studies analyzing the relationship between VO_2 and GME during prolonged constant-load cycling exercise (18), no data are available about the VO_{2sc}, EE, HSE, or GME of humans able to sustain 21 sets of 15 repetitions for at least 31 minutes with relatively low circulating lactate levels (~3.3 mMol) in HS exercise.

Our results were slightly higher in absolute values (153.8 ml in 28 minutes vs. 130 ml in 17 minutes) and slightly lower in relative values (5.49 ml·min^{-1} vs. about 8 ml·-min^{1}) than those obtained by professional cyclists (22), although our findings clearly differed from those reported by others (330 ml in 15 minutes or 22 ml·min^{-1}) in nonprofessional cyclists (17), both studies during 20 minutes of constant-load test at 80% of VO_{2max}. Carter et al. (6) found that the absolute magnitude of VO_{2sc} was significantly higher for cycling than for running at 2 intensities (50%Δ, 334 ± 183 vs. 205 ± 84 ml·min^{-1}; 75%Δ, 430 6± 159 vs. 302 ± 154 ml·min^{-1}). These data verify the assumptions that the precise amplitude of VO_{2sc} is influenced by the experimental conditions, characteristics of the participants including fitness and muscle fiber type (2,33), exercise modalities (19), training status (22), and the exercise intensity (5).

Although similar VO_{2sc} performance could be observed in different exercise modalities (i.e., HS in our study vs. cycling), the etiology of resistance exercise at LT intensity is uncertain because the power output at LT intensity signifies the highest power output or load that will not induce VO_{2sc} intensity (5). In theory, at LT intensity, the VO_{2sc} should be nonexistent or very low; however, in our study, a slow rise of VO_{2sc} was observed, similar to that reported in professional cyclists at an intensity above LT (80% VO_{2max}) (22).

Although our study did not compare HS to cycling exercises, we suspected that HS exercise could induce higher levels of fatigue than cycling at the same relative intensity (LT), elevating the VO_{2sc}; this idea is supported by our previous findings (13) that significant losses in jump capacity height and power output production occur only in HS exercise and not in cycling at the end of constant-load testing at LT intensity. Again, this study corroborates a mechanical fatigue (approx. losses of 5% in height and power) induced in lower limbs evaluated by CMJ capacity immediately after constant-load HS exercise test at LT intensity. We suggest a causal relationship between the mechanical mechanisms that induce loss of force in lower extremities and the increased O2 cost of exercise at the end of constant-load test. The increased VO_{2sc} cost of exercise likely appears at intensities at which muscle fatigue has been reported (9). Probably, ATP cost of muscle contraction progressively increased while force production of lower limbs was gradually decreasing (4) throughout the constant-load HS test. Thus, the intensity-dependent decline in muscle efficiency is believed to be associated with the progressive development of muscle fatigue (45).

In addition, Poole et al. (33) proposed that 86% of the VO_{2sc} could be determined by an increase in leg oxygen uptake, suggesting that VO_{2sc} is mainly activated within the contracting muscle, and the central factors have a minor influence of its amplitude (29). From a mechanical perspective, this means a delayed recruitment of less oxidatively efficient, larger motor units to compensate for attenuated force production in those already active motor units (12), as well as a reduction in the efficiency of skeletal muscle contraction or/and mitochondrial energy production (20). In support of this assumption, the magnitude of VO_{2sc} has been correlated with the percentage (2) and recruitment of type II muscle fibers (37). It has been assumed that the ratio of phosphate produced per oxygen consumed is 18% higher in isolated mitochondria from type I compared with type II muscle, which suggests uncoupling of mitochondrial respiration (44). In this regard, VO_{2sc} reveals a gradual recruitment of type II fibers with exercise duration (33,35), whereas type II fibers are less efficient than type I fibers. The purpose of this study was not to assess the physiological mechanisms responsible for the gradual recruitment of type II fibers; therefore, these assumptions are purely speculative. However, some of these physiological mechanisms may justify the need for recovery time in resistance exercises to continue maintaining a predominantly aerobic metabolism at LT intensity.

The exact mechanisms that cause VO_{2sc} during submaximal intensity exercise are not yet fully understood. We hypothesized that the VO_{2sc} phenomenon might be explained, at least in part, by the change in GME, which estimates the effects of blood alkalinization on the gradual loss of muscle efficiency (12).

Unfortunately, our results cannot be reinforced by previous findings because no data are available about GME and efficiency in resistance exercises during long-term constant-load exercise testing at LT intensity. The GME results reported in this study are higher than those obtained in world class cyclist (23) and professional riders (24) (both ~24%) at the power outputs eliciting the LT and the respiratory compensation point during a ramp test. In well-trained cyclists were observed lower values (~18%) during 2-hour constant-load cycling exercise at 60% of maximal minute power output (18). Other studies in cyclists who were not highly trained (30) have found lower values of GME (~20%) in healthy general population, values of 18–22% have been observed, and values of 16% were reported in chronic patients with severe exercise intolerance during leg cycling exercise (1).

The physiological mechanisms of GME reduction in resistance exercises during constant-load test at LT intensity are fully unknown. The high values found in our study, compared with others, are likely attributable to the characteristics of resistance training. Performing a set of HS or other resistance exercise is usually a brief and intense task in which recovery time is required to execute added series. Probably, making 21 sets of HS exercise causes a relative lack of O_2 supply to muscle loci, further suggesting that a large portion of the energy comes from anaerobic system that could not be determined by measuring metabolic gas exchange. This may have happened from a theoretical perspective because resistance training is chiefly fueled by anaerobic metabolism, generally inducing an important release of anaerobic sources to EE (40) that preclude the use of steady-state VO_2 to accurately estimate EE (36). As a result, a high-efficiency ratio (work accomplished/EE) could occur.

In addition, Villagra et al. (41) found a higher VO_2 and a lower GME (approximately 13–20%) as the load increased in 2 forms of squatting exercise. Gross mechanical efficiency differences observed between our results and those of Villagra et al. (41) could be attributed to the experimental protocols used in both studies. Participants in their study performed 24 knee flexions per minute and 96 flexions in 4 minutes with full recovery between sets in 2 forms of squatting exercise. In our study, unlike several studies that used different resistance exercises and protocols (10,38), an experimental protocol of 15 repetitions/30 seconds per set was achieved in which blood lactate levels and VO_2

responses remained stable during HS constant-load test at LT intensity (13,14). In both studies, light loads were used, and therefore, the differences could be produced by the repetitions/duration established in each set and the type of exercise (HS vs. full squat). In preliminary test, we detected that the blood lactate concentrations and VO_2 were exponentially increased by rising the repetitions/duration (approximately more than 20 repetitions or 35–40 seconds per series). It can reasonably be expected that if a set of 1 minute in squatting exercises is performed (41), probably, EE will mostly come from anaerobic sources to a greater extent than in our study, triggering a different oxygen consumption and GME. We advocate a protocol of 15 repetitions/30 seconds per set to request mostly aerobic sources in a constant protocol. These postulates should be supported by other experimental designs that analyze the etiology of GME in resistance exercises in both aerobic and anaerobic metabolism.

Significantly higher lactate values were observed during the HS exercise than at baseline, but once they had increased to ~3.3 $mmol \cdot L^{-1}$ at S3, there were no further increases, although GME and HSE were smoothly diminishing as the VO_2 was slowly rising as the time of the test was extended. Effectively, an inverse relationship between GME and ΔVO_2 was observed. It has been reported that a decrease in efficiency coincides with significant increases in oxygen uptake during repeated submaximal exercise (32).

Other possible explanations that would justify the high GME observed could be related to the stretch-shortening cycle in HS exercise. The stretch shortening cycle involves the active stretching of a muscle (eccentric contraction) followed by its immediate shortening (concentric contraction). Previous findings (41) have demonstrated that the gross, net, and apparent efficiency of rebound squats was significantly greater than that of no rebound squats. The authors concluded that the mechanical work performed in both protocols (rebound vs. no rebound) was the same; however, no rebound exercise induced a greater oxygen cost. It is likely that the rebound HS exercise requires less oxygen due to the contribution of elastic recoil (41). During eccentric phase (prestretching or negative work), a storage of elastic energy in the series elastic components is produced in muscles and tendons. Energy produced is reused during the concentric phase (positive work), possibly decreasing oxygen uptake to a greater extent than resistance exercises with a single concentric phase.

Most of the studies used to evaluate GME have been in cycling test, and cycle pedaling mainly involves concentric muscle actions (11). Various factors affect efficiency and fatigue during exercise, including muscle properties (22), the type of muscle contraction, the type of muscle action, and the exercise methodology (maximal vs. submaximal force generation and duration) (26). Studies comparing GME of the cycle ergometer and resistance exercise are needed to sustain such claims. In addition, differences in power measurement between a linear position transducer and a cycle ergometer should be taken into consideration.

Although GME might be linked to the percent distribution of oxidative, fatigue-resistant (type I) fiber, it certainly is not an accurate measure of muscle efficiency (8). However, GME could be considered as a practical and suitable marker of whole-body efficiency (7), reliable throughout laboratory tests (30), reflecting the ability to perform exercise at the lowest possible metabolic cost.

This study had some limitations that need to be discussed. The 1RM of the subjects could vary from the initial test session to the next; therefore, a test-retest would have been convenient for improving reliable test results by reducing the effects of a systematic bias. This means that the load used (%1RM) during incremental test session and the power output developed in each repetition of HS exercise could also be slightly altered during the constant-load test at LT intensity.

Future research should be conducted to determine what type of exercises (resistance and/or endurance exercises) could be more efficient to apply both in sports performance and in health-related exercise programs in diverse populations (e.g., healthy adults, sedentary lifestyle, elderly, athletes, diseases, etc.). It would be essential to analyze other resistance exercises (e.g., bench press, leg press, etc.) and compare or combine them with endurance exercises (e.g., cycling, walking, running, etc.) to determine what type of exercises are more suitable for each population according to the objective of the exercise program.

PRACTICAL APPLICATIONS

The etiology of fatigue in resistance exercise is not completely understood. However, better knowledge of the behavior of VO_{2sc}, EE, HSE, and GME (typically used in endurance exercises) would allow us to increase performance and discover the potential of resistance exercises in a predominantly aerobic metabolism.

Although no studies have been conducted applying resistance training programs at LT intensity, it is plausible to speculate that resistance training at LT intensity could be a very useful complementary training at a certain time of the season, especially when we refer to fitness training programs and sport performance by improving local muscular resistance and/or cardiorespiratory fitness in both athletes and healthy adults. It is likely that when performing 21 series in resistance exercises with a short recovery time as described in this study, local muscle endurance could be improved using a predominantly aerobic metabolism without producing the metabolites (e.g., H^+) that generate the most purely anaerobic metabolism. It is suspected that, by the decrease in jumping ability, the load used in resistance exercises at LT intensity may be great enough to increase local muscle endurance. In preliminary tests (unpublished data), our research group have observed how the combination of resistance exercises in a circuit training at LT intensity could maintain stable and low blood lactate concentrations, slightly increasing the VO_{2sc} and maintaining a high mechanical efficiency. More research is needed to confirm these preliminary findings.

A further possible application could be the prescription of resistance exercises in patients with some sort of disorder. For example, resistance training conducted at an intensity equivalent to the LT would help optimize glucose entry into the muscle, probably improving cardiorespiratory fitness and local muscle endurance.

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8. ARTÍCULO 2

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The Slow Component of Oxygen Uptake and Efficiency in Resistance Exercises: A Comparison With Endurance Exercises

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ABSTRACT

Introduction

There is a lack of information regarding the slow component of oxygen uptake (VO_{2sc}) and efficiency/economy in resistance exercises despite the crucial role played in endurance performance.

Purpose

this study aimed to compare the VO_{2sc}, efficiency/economy, metabolic, cardiorespiratory responses, rating of perceived effort and mechanical fatigue between cycling and half-squat (HS) exercises during a constant-load test at lactate threshold (LT_1) intensity.

Methods

Twenty-one healthy men were randomly assigned in a crossover design to perform cycle-ergometer or HS tests. The order of the two cycle ergometer tests was an incremental test for determining load-intensity in watts (W) at LT_1, followed by a constant-load test at the LT_1 intensity. For the three HS tests, the order was a 1RM test to determine the load (kg) corresponding to the 1RM percentages to be used during the second test, incremental HS exercise to establish the load (kg) at the LT_1 intensity, and finally, a constant-load HS test at the LT_1 intensity. A rest period of 48 h between each test was established. During the HS and cycle-ergometer constant-load tests, cardiorespiratory and metabolic responses were recorded. Lower limbs fatigue was determined by a jump test before and after the constant-load tests.

Results

A significant exercise mode × time interaction effect was detected in VO_2, heart rate, energy expenditure (EE), gross efficiency (GE), and economy ($p < 0.05$). A significant and sustained VO_2 raise was confirmed in HS exercise ($p < 0.05$) and a steady-state VO_2 was revealed in cycle-ergometer. A higher GE and economy were obtained in HS test than in cycle-ergometer exercise ($p < 0.001$). In both exercises, a non-significant decrease was observed in GE and economy ($p > 0.05$). Lower limbs fatigue was only detected after constant-load HS test.

Conclusion

Although the VO_2, heart rate and EE responses were higher in cycling exercise, the constant-load HS test induced a greater VO_{2sc} and EE raise than the cycling test in a predominantly aerobic metabolism. These results could explain a decrease observed in jump performance only after HS test. GE and economy could benefit from the eccentric phase of the HS exercise.

Keywords: oxygen uptake kinetics, gross efficiency, energy expenditure, lactate threshold, mechanical fatigue

INTRODUCTION

Laboratory testing of respiratory exchange using a breath-by-breath open-circuit gas analyzer have become a fundamental practice for measuring oxygen uptake (VO_2) kinetics during constant-load endurance exercises. Pulmonary VO_2 tends to rise slowly for a given power output beyond ~3 min during prolonged constant-load endurance exercise, involving sustained lactic acidosis; this surpasses the primary component initiated at exercise onset. This ventilatory phenomenon is known as the slow component of VO_2 (VO_{2sc}) (Gaesser and Poole, 1996).

As some authors suggest, the VO_{2sc} could be affected by the behavior of various parameters such as the power-load, VO_2, and lactate threshold (LT), conditioning cardiorespiratory performance and efficiency (Burnley and Jones, 2007). The power output developed above, below or at the LT will determine the amplitude of the VO_{2sc} response. Therefore, LT intensity plays a key role in the assessment of VO_{2sc}. According to three-phase model (Skinner and McLellan, 1980), two LTs (LT_1 and LT_2) are recognized during cardiopulmonary exercise testing (Binder et al., 2008). LT_1 is considered as "aerobic threshold" at 40–60% of VO_{2max} (light exercise), and LT_2 is discerned as "anaerobic threshold" at 60–90% of VO_{2max}(moderate to heavy exercise). Obviously, the VO_{2sc} at LT_2 intensity will increase to a greater extent than at LT_1 intensity during constant-load exercise.

Despite the important role of VO_{2sc} in endurance performance (Lucía et al., 2002), respiratory exchange tests for evaluating power output or VO_2 at the LT_1 intensity are not usually applied to resistance exercises in laboratory conditions and, therefore, there is a surprising lack information about VO_{2sc}. To date, only one recent study has focused on VO_{2sc} in resistance exercises at the LT_1 intensity (Garnacho-Castaño et al., 2018a). Two findings of this study draw the attention. Firstly, the authors reported a slightly higher VO_{2sc} in absolute values (153.8 mL.min^{-1}), during 31 min of constant-load HS testing at the LT_1 intensity in healthy young practitioners, compared to that reported in another study with professional cyclists (130 mL.min^{-1}) during 20 min of constant-load test at an intensity above LT_1 (80% VO_{2max}) (Lucía et al., 2000). This detected response of VO_{2sc} usually occurs at intensities above the LT_1 in endurance exercises (Burnley and Jones, 2007). It could be that the VO_{2sc} in HS exercise, in a mainly aerobic metabolism (LT_1), is comparable to the VO_{2sc} observed in endurance exercises at intensities above the LT_1. It has been shown that VO_{2sc} is lower in a leg cycle compared to an arm crank exercise (Koppo et al., 2002) and higher in cycling than in running exercise (Billat et al., 1998). This difference between the exercise modes was chiefly associated with the amplitude of response (Carter et al., 2000), which in turn was conditioned by loading intensity during constant-load test (Carter et al., 2002). So, the VO_{2sc} is exercise- and intensity-dependent.

Secondly, the authors demonstrated that the continuous increase in VO_2 and energy expenditure (EE) was linked to a decrease in gross efficiency (GE) (Garnacho-Castaño et al., 2018a). In addition, lower limbs fatigue was detected after constant-load HS test. The VO_{2sc} could be explained, at least partly, by the variation in GE which assesses the effects of blood alkalinization on the gradual loss of muscle efficiency (Gaesser and Poole, 1996) and progressive fatigue (Garnacho-Castaño et al., 2018a).

Keeping these two premises in mind, it appears reasonable to suggest a greater increase in VO_{2sc} and EE, whereas the efficiency decrease, during HS exercise than during a constant-load cycling test at the LT_1intensity. In theory, the power output or load equivalent to the LT_1 intensity means the highest power output or load that will not elicit VO_{2sc} (Burnley and Jones, 2007) during constant-load endurance tests. However, to the best of our knowledge, no studies have compared VO_{2sc}, GE, EE, and mechanical fatigue between resistance and endurance exercises during long-term constant-load test at the same aerobic metabolic intensity (LT_1).

To compare VO_{2sc} and efficiency between resistance and endurance exercises could provide relevant information for clarifying the underlying physiological mechanisms that related VO_{2sc} and EE to efficiency and fatigue in resistance exercise and, therefore, to determine whether resistance or endurance exercises are more efficient in a predominantly aerobic metabolism. This study aimed to compare VO_{2sc}, efficiency/economy, metabolic responses and mechanical fatigue between cycling and HS exercises during a constant-load test at an intensity corresponding to LT_1.

MATERIALS AND METHODS

Participants

Twenty-one healthy participants were recruited among the male students of the Physical Activity and Sports Sciences Department (age: 21.4 ± 1.5 years, height: 180.2 ± 5.4 cm, weight: 81.8 ± 8.6 kg, body mass index: 25.2 ± 2.0). All participants had at least 6 months of experience in resistance training and were accustomed to HS exercise.

Four exclusion criteria were established: (1) any cardiovascular, metabolic, neurological, pulmonary or orthopedic disorders that could limit exercise performance, (2) the use of any medication, supplements, or performance-enhancing drugs, (3) a one-repetition maximum (1 RM) of less than or equal to 150 kg in HS exercise, (4) being an elite athlete.

Eligible participants were informed of the tests they would be taking, and provided their signed written consent to participate. The participants were instructed to refrain from other exercises or resistance training during the course of the study. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Ethics Committee of TecnoCampus-Pompeu Fabra University (Mataró, Barcelona, Spain).

Experimental Design

Subjects were required to visit the laboratory on five occasions at the same time each day under similar environmental conditions (temperature 21–25°C, atmospheric pressure 715–730 mm Hg, relative humidity ~45%). The protocols were implemented according to the procedures previously established by our research group (Garnacho-Castaño et al., 2015a). Participants were randomly assigned in a crossover design to perform cycle ergometer or HS tests.

The order of the two cycle ergometer tests was an incremental test for determining load-intensity in watts (W) at LT_1, followed by a constant-load test at the LT_1 intensity. For the three HS tests, the order was a 1RM test to determine the load (kg) corresponding to the 1RM percentages to be used during the second test, incremental HS exercise to establish the load (kg) at the LT_1 intensity, and finally, a constant-load HS test at the LT_1 intensity.

A rest period of 48 h between each test was established. During the HS and cycle ergometer constant-load tests, acute cardiorespiratory and metabolic responses were recorded. Timing of blood lactate sampling was the same in both tests. Before and after the constant-load tests, mechanical fatigue in the lower limbs was determined by a counter movement jump (CMJ) test.

Cycle Ergometry Tests

Incremental and constant-load cycle ergometer tests included a 5-min warm-up on a cycle ergometer (Monark ergomedic 828E, Vansbro, Sweden) at an initial pedaling cadence of 50 rev.min^{-1} and work rate of 50 W, followed by 5 min of dynamic joint mobility drills and stretching exercises. After 2-min rest time, the cycle ergometer tests commenced. In both tests, blood lactate concentrations were measured using a portable lactate analyzer (Lactate Pro LT-1710, Arkray Factory Inc., KDK Corporation, Siga, Japan). The reliability of this device has been previously evaluated (McNaughton et al., 2002).

The incremental test was carried out in a ramp protocol starting with a load of 50 W, which was increased in steps of 25 W.min^{-1} until completing 8 min at a pedaling cadence of 50 rev.min^{-1}. Blood samples (5 µL) were attained by finger pricking at rest and every 2 min during the incremental test. The LT_1 was determined according to three-phase model (Skinner and McLellan, 1980), following the guidelines established by Binder et al. (2008). The LT_1 was detected by inspecting blood lactate concentrations plotted against workload according to the protocol described by Weltman et al. (1990). The LT_1 was defined as the highest exercise load completed when a 0.5 mmol.L^{-1} rise over baseline is detected in at least 2 instances.

The constant-load cycle ergometer test involved continuous pedaling at a cadence around 70–80 rev.min^{-1} at an intensity (W) equivalent to the LT_1 previously determined in the incremental test. The test duration was 31 min. Blood lactate samples were obtained at the start of the test and at the following minutes of cycling: min 4, min 8.5, min 13, min 17.5, min 22, min 26.5, and min 31. Respiratory exchange data were recorded during the constant-load test using a breath-by-breath open-circuit gas analyzer (Vmax spectra 29, Sensormedics Corp., Yorba Linda, CA, United States), which had been previously calibrated. VO_2, minute ventilation (VE), carbon dioxide production (VCO_2) and respiratory exchange ratio (RER) were monitored. Heart rate was checked every 5 s by telemetry (RS-800CX, Polar Electro OY, Finland).

Half Squat Tests

In HS tests, a Smith machine (Matrix Fitness, Johnson Health Tech, Cottage Grove, MN, United States) was used to ensure controlled movements. Each HS test started with a warm-up consisting of 5 min of low intensity running and 5 min of joint mobility. This was followed by a specific warm-up consisting of 1 set of 3–5 repetitions (HS) at a relative intensity of 40–60% of the maximum perceived effort. After 2-min, HS test protocols commenced.

Establishing the 1RM involved 3–5 lifting attempts using increasing weight. The 1RM was defined as the last load lifted by the subject, completing a knee extension to the required position. The rest period between each attempt was 4 min (Garnacho-Castaño et al., 2018a).

The incremental HS test was carried out in 5 sets at relative intensities of 10, 20, 25, 30, 35, and 40% 1RM as previously described (de Sousa et al., 2012; Garnacho-Castaño et al., 2015a,b, 2018a). Each set lasted 1 min and involved 30 repetitions of 2 s each (1 s for both eccentric and concentric muscle actions). This rhythm was checked with a metronome while a researcher provided visual and verbal cues. A passive rest period of 2 min between sets (Garnacho-Castaño et al., 2015a,b) was provided while blood samples were collected for LT_1 and the load was augmented. The test was terminated voluntarily by the participant or when he was powerless to continue performing repetitions at the set cadence or did not correctly execute repetitions. Blood samples (5 µL) were obtained by finger pricking 30 s after the end of each set, and lactate levels were measured using the same portable lactate analyzer.

The LT_1 was recognized by means of the algorithm adjustment method based on Orr et al. (1982) as the load-intensity at which blood lactate concentrations start to increase in an exponential manner (Wasserman and McIlroy, 1964). The LT_1 was detected through computerized 2-segment linear regression by fixing the 2 linear regression equations emerging for each segment at the point of intersection between a plot of blood lactate concentration and relative intensity. Data analysis was performed using Matlab version 7.4 (MathWorks, Natick, MA, United States).

The constant-load HS test was conducted as 21 sets of 15 repetitions of 2 s each (1 s for both eccentric and concentric phases) guided by metronome, visual, and verbal cues. The duration of each set was 30 s and the rest period between sets was 1 min. These guidelines were established in preliminary trials and, subsequently, in previous studies (Garnacho-Castaño et al., 2015a,b). In the constant-load test, it was not possible to perform HS sets in a time longer than 30 s. Furthermore, a recovery period of less than 60 s between sets could not be standardized because in both cases the blood lactate concentrations increased exponentially.

The whole constant-load test took 31 min. Respiratory exchange and heart rate data were recorded as previously described (Garnacho-Castaño et al., 2015a,b). Blood samples were obtained at rest and 30 s after the end of the HS sets (S) S3, S6, S9, S12, S15, S18, and S21, when lactate concentrations were obtained as described above for the incremental test.

VO_2 Slow Component, Efficiency/Economy in Constant-Load Tests

In both HS and cycle constant-load tests, the VO_{2sc} was identified as the difference between end-of-exercise VO_2 and the VO_2 at the end of the third minute of constant-load exercise (Δ VO_2, in $mL.min^{-1}$). The latter was taken as the average VO_2 from 2 min 30 s to 3 min 30 s (set 2 to set 3); end-exercise values were taken as the average of the last 2 min of the tests (29 min 0 s to 31 min 0 s, set 20 to set 21). Mean cycling- (CE) and HS-economy (HSE) was expressed in $W.L^{-1}.min^{-1}$. GE was calculated as the ratio of work accomplished per minute (i.e., W in $kcal.min^{-1}$) to energy consumed per minute (i.e., in $kcal.min^{-1}$) as follows:

GE(%)=(Workaccomplished/EE)×100.

The mean power output during the same period as the respiratory exchange collection was recorded in order to determine "Work accomplished," which was converted into $kcal.min^{-1}$ as follows:

Workaccomplished(kcal.min−1)=Poweroutput(W)×0.01433.

Energy expenditure was calculated from VO_2 and the RER. The calorific equivalent of O_2 was determined from the corresponding RER, using the tables provided by Peronnet and Massicotte (1991).

EE(kcal.min−1)=VO2(L.min−1)×Kcal.L−1ofO2.

The power output to quantify HSE and GE during HS test was calculated by means of a reliable and validated linear position transducer (Tendo Weight-lifting Analyzer System, Trenèín, Slovakia) (Garnacho-Castaño et al., 2015c). The power output was computed in each repetition based on bar velocity (Lake et al., 2012). The mean power output was calculated as the mean of all repetitions.

Lower Limbs Mechanical Fatigue

Lower limbs fatigue was evaluated in a CMJ test using a force plate (Quattro Jump model 9290AD; Kistler Instruments, Winterthur, Switzerland), as previously described (Garnacho-Castaño et al., 2015a,b). Jump height, mean power, and peak power were recorded before the start and at the end of both constant-load tests, immediately after the last blood lactate reading. Participants carried out 3 jumps and the mean height, mean power, and peak power output were used in the data analysis. A recovery period of 30 s between each jump was established.

Perceived Effort

The Borg scale was used to monitor the rating of perceived effort (RPE) (Borg, 1978). Scores were recorded by each subject at the blood collection time points for blood lactate determination during incremental and the constant-load tests.

Statistical Analysis

The Shapiro–Wilk test was used to check the normal distribution of data, provided as means, standard deviation (SD), confidence intervals (95% CI) and percentages. To identify significant differences between HS and cycle ergometer exercises in VO_2 kinetics, lactate levels, and economy/efficiency variables during constant-load tests, a general linear model with a two-way analysis of variance (ANOVA) for repeated measures was performed. The two factors were exercise mode (HS and cycle ergometer) and time (corresponding to 7 checkpoints performed in both tests). When appropriate, a Bonferroni *post hoc*adjustment for multiple comparisons was implemented. To determine mechanical fatigue, an ANOVA for repeated measures was performed. A Student's *t*-test was used to compare heart rate, VO_2, RPE and blood lactate concentrations at LT_1 intensity during incremental test in cycle ergometer and HS exercises.

Partial eta-squared (η2p) was computed to determine the magnitude of the response to both exercise modes. The statistical power (SP) was also calculated. Intraclass correlation coefficients and coefficients of variation percentage were used to determine the relative and absolute reliability. All statistical methods were performed using the software package SPSS Statistics version 23.0 for Mackintosh (SPSS, Chicago, IL, United States). Significance was set at $p < 0.05$.

RESULTS

Descriptive data related to incremental-load test in cycle ergometer and HS exercises are presented in Table 1. Differences in VO_2, heart rate, metabolic, RPE and economy/efficiency responses between HS vs. cycle ergometer during constant-load tests are shown in Table 2. Mean intraclass correlation coefficient and mean coefficient of variation for all VO_2, metabolic and economy/efficiency variables was 0.982 (0.966–0.991) and 5 ± 2%, respectively.

Table 1. Data related to 1RM- and incremental-load test

Variables	**HS**	**CYC**
1RM (Kg)	200.3 (39.7)	-
HS load at LT_1 (kg)	49.6 (16.2)	-
Relative intensity at LT_1 (%1RM)	23.9 (4.8)	-
Load at LT_1 (W) *.	242.6 (86.9)	3. 168.1 (38.2)
VO_2 at LT_1 ($mL·kg^{-1}·min^{-1}$) $^{\delta}$	2.08 (0.32)	1.96 (0.37)
Lactate at LT_1 ($mmol·L^{-1}$) $^{\delta}$	2.51 (0.59)	2.21 (0.51)
HR ($beats·min^{-1}$) $^{\delta}$	134.95 (16.84)	125.43 (17.16)
HR (%) $^{\delta}$	63.14 (8.53)	67.96 (8.60)
RPE (6-20) $^{\delta}$	10.62 (1.80).	9.81 (2.09)

Data are presented as mean and standard deviation (SD). 1RM, one-repetition maximum; CYC, cycle-ergometer; HR, heart rate; HR (%), percentage regards theoretical maximum heart rate; HS, half-squat; LT_1, lactate threshold one; RPE, rating of perceived exertion; VO_2, oxygen uptake. *Significant differences between HS and cycle ergometer. $^{\delta}$No significant differences between HS and cycle ergometer.

VO_2, Lactate, RPE and Heart Rate Responses at LT_1 during Incremental Tests

No significance differences were found between cycle ergometer and HS exercises in VO_2, lactate, RPE and heart rate responses at LT_1 during incremental tests ($p > 0.05$).

Table 2. Differences in VO_2, metabolic and economy/efficiency responses between half-squat vs cycle-ergometer during constant-load test at lactate threshold intensity

	HS (95% CI)	CYC (95% CI)	P^1 ES/SP	P^2 ES/SP	P^3 ES/SP
VO_2 ($L.min^{-1}$)	1.60	2.26	**< 0.001**	**< 0.001**	0.001
	(1.51-1.68)	(2.06-2.46)	0.56/1.00	0.64/1.00	0.17/0.97
RER	0.94	0.92	**< 0.001**	0.22	0.88
	(0.92-0.95)	(0.90-0.94)	0.44/1.00	0.07/0.22	0.02/0.16
Lactate ($mmol.L^{-1}$)	3.29	3.13	0.67	0.58	0.17
	(2.90-3.69)	(2.49-3.78)	0.03/0.26	0.03/0.08	0.07/0.60
VO_{2sc} ($L.min^{-1}$) (at each checkpoint)	0.09	0.05	0.10	**< 0.001**	**0.03**
	(0.05-0.12)	(0.03-0.08)	(0.13-0.37)	(0.35-1.00)	(0.11-0.82)
EE ($Kcal.min^{-1}$)	7.93	11.19	**< 0.001**	**< 0.001**	**0.001**
	(7.48-8.37)	(10.19-12.19)	0.575/1	0.631/1	0.165/0.965
GE (%)	43.49	17.66	**< 0.001**	**< 0.001**	**0.005**
	(37.65-49.33)	(15.62-19.69)	0.531/1	0.754/1	0.142/0.924
EC ($W.L^{-1}.min^{-1}$)	150.78	60.91	**< 0.001**	**< 0.001**	**0.013**
	(130.46-171.11)	(69.07-86.73)	0.485/1	0.755/1	0.125/0.875

Abbreviations used: CYC: cycle-ergometer; EC: economy; EE: energy expended; ES: effect size; GE: gross efficiency; HS: half-squat; L: liter; min: minute; RER: respiratory exchange ratio; SP: statistical power; VO_2: oxygen uptake; VO_{2sc}: slow component of oxygen uptake; W: watt. P^1 Significant differences for time effect. P^2 Significant differences for exercise mode effect. P^3 Significant differences for exercise mode x time interaction effect. Data are provided as mean and 95% confidence intervals (95% CI).

VO_2, Heart Rate, Respiratory Exchange Ratio, Lactate and RPE During Constant-Load Tests

In VO_2, a significant exercise mode x time interaction effect was observed [$p = 0.001$, $F_{(6,120)} = 4.05$, $\eta 2p = 0.17$, SP = 0.97]. A significant time effect [$p < 0.001$, $F_{(6,120)} = 25.06$, $\eta 2p = 0.56$, SP = 1.00], and exercise mode effect were detected [$p < 0.001$, $F_{(1,20)} = 35.14$, $\eta 2p = 0.64$, SP = 1.00]. After Bonferroni adjustment of multiple comparisons, a significant and sustained VO_2 raise was confirmed from S3 in HS exercise ($p < 0.05$) and a steady-state pulmonary VO_2 was revealed from M4 in cycle ergometer. Higher VO_2 was found in cycle ergometer than HS exercise at each checkpoint (*p* < 0.001) (Figure 1)

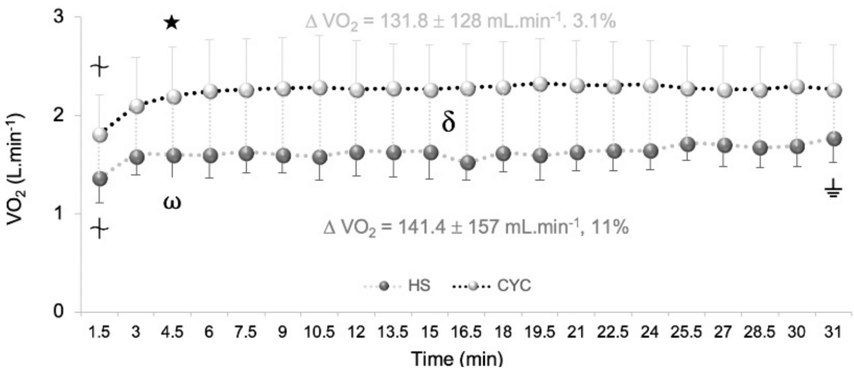

FIGURE 1

Differences in slow component of oxygen uptake (VO_{2sc}) between half-squat (HS) exercise and cycle ergometer (CYC) during constant-load test. ω Significantly different from S6 (p = 0.027), S18 (p = 0.001), and S21 (p = 0.001). ⏚ Significantly different from S3 (p = 0.001), S6 (p = 0.043), and S12 (p = 0.003). ★ Significantly different from M8.5, M13, M17.5, M22, M26.5, and M31 (p < 0.001). δ Significant differences between cycle ergometer and HS exercise at each checkpoint (p < 0.001).

In heart rate, a significant exercise mode x time interaction effect was detected [$p < 0.001$, $F_{(6,120)} = 8.30$, η2p = 0.29, SP = 1.00]. A significant time effect [$p < 0.001$, $F_{(6,120)} = 34.69$, η2p = 0.63, SP = 1.00], and exercise mode effect were detected [$p < 0.001$, $F_{(1,20)} = 30.14$, η2p = 0.60, SP = 0.99]. Bonferroni test determined a higher heart rate in cycle ergometer than HS exercise at each checkpoint (*p* < 0.001) (Figure 2).

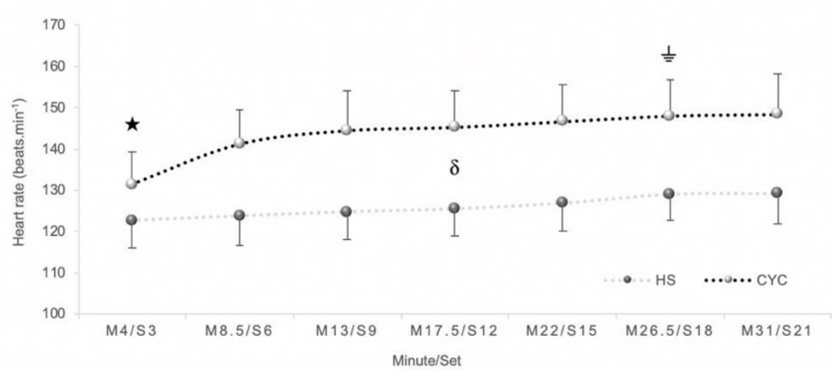

FIGURE 2

Differences in heart rate between half-squat (HS) exercise and cycle ergometer (CYC) during constant-load test. ★ Significantly different from M8.5, M13, M17.5, M22, M26.5, and M31 (p < 0.001). ⏚ Significantly different from M3, M8.5, M17.5, and M22 (p = 0.05). δ Significant differences between cycle ergometer and HS exercise at each checkpoint (p < 0.01).

No significant exercise mode x time interaction effects or time and exercise mode effects were detected in lactate concentrations (p > 0.05) (Figure 3A). It was only detected a time effect in RER [$p < 0.001$, $F_{(6,120)}$= 15.89, η2p = 0.44, SP = 1.00] (Figure 3B) and RPE [$p < 0.001$, $F_{(6,120)}$ = 32.88, η2p = 0.62, SP = 1.00].

VO_{2sc}, Energy Expenditure, Gross Efficiency and Economy During Constant-Load Tests

In VO_{2sc} at each checkpoint, a significant exercise mode × time interaction effect was observed [$p = 0.027$, $F_{(6,114)}$ = 2.48, η2p = 0.11, SP = 0.82], along with a significant time effect [$p < 0.001$, $F_{(6,114)}$ = 10.61, η2p = 0.35, SP = 1.00]. Bonferroni adjustment of multiple comparisons confirmed a greater VO_{2sc} in HS than in cycle ergometer testing at the end of exercise (M22/S15, M31/S21) ($p < 0.05$) (Figure 4A).

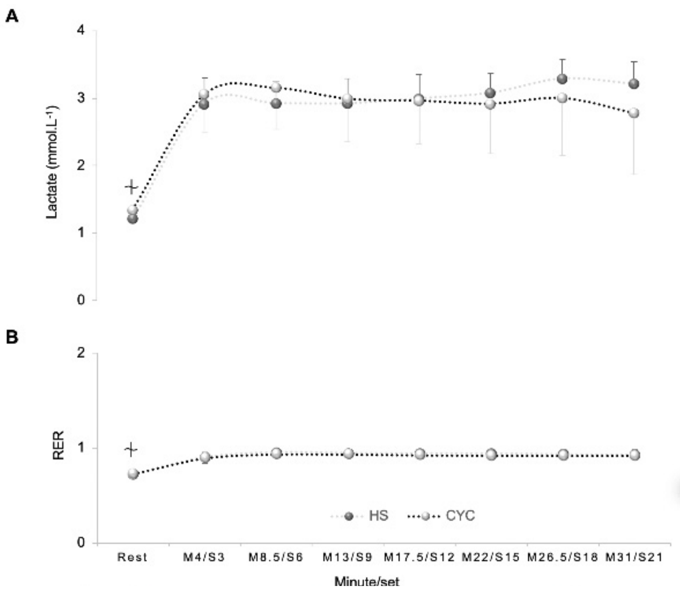

FIGURE 3

Differences between half-squat (HS) exercise and cycle ergometer (CYC) during constant-load test in: **(A)** Blood lactate. **(B)** Respiratory exchange ratio (RER). No significant differences between cycle ergometer and HS exercises (p > 0.05). Significantly different from M8.5, M13, M17.5, M22, and M26.5 in cycle ergometer (p < 0.05) and significantly different from M8.5, M13, and M17.5 in HS exercise (p < 0.01).

In EE, a significant exercise mode × time interaction effect was discovered [p = 0.001, $F_{(6,120)}$ = 3.96, η2p= 0.17, SP = 0.97]. A significant time effect [$p < 0.001$, $F_{(6,120)}$ = 27.10, η2p = 0.58, SP = 1.00] and exercise mode effect were identified [p < 0.001, $F_{(6,120)}$ = 34.25, η2p = 0.63, SP = 1.00]. Bonferroni *post hoc* analysis confirmed a higher EE in cycle ergometer than HS exercise at each checkpoint ($p < 0.001$). A slight and continued EE increase was detected from S3 in HS exercise ($p < 0.05$). A stable EE was observed from M4 in cycle ergometer ($p > 0.05$) (Figure 4B).

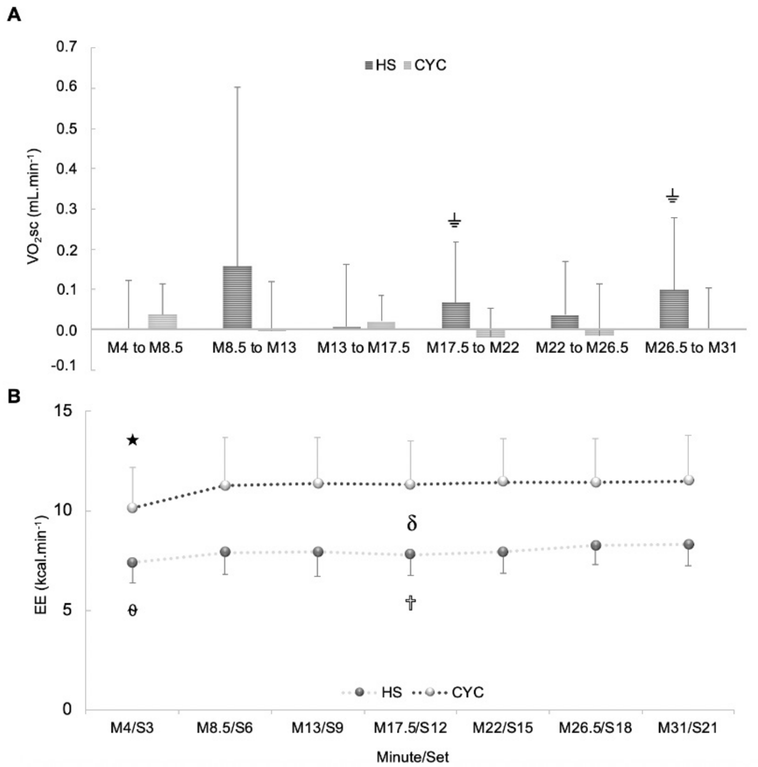

FIGURE 4

Differences between half-squat (HS) exercise and cycle ergometer (CYC) during constant-load test at each checkpoint: (A) Slow component of oxygen uptake (VO_{2sc}). (B) Energy expenditure (EE). ★ Significantly different from M8.5, M13, M17.5, M22, M26.5, and M31 (p < 0.001). ϴ Significantly different from S6, S15, S18, and S21. † Significantly different from S21. δ Significant differences between cycle ergometer and HS exercise at each checkpoint (p < 0.001). ⏚ Significantly different from cycle ergometer (p < 0.05).

In GE, a significant exercise mode x time interaction effect was discovered [p = 0.005, $F_{(6,120)}$ = 3.31, η2p= 0.14, SP = 0.92]. In addition, a significant exercise mode and time effect was found [p < 0.001, $F_{(1,20)}$ = 61.41, η2p = 0.75, SP = 1.00; p < 0.001, $F_{(6,120)}$ = 22.65, η2p = 0.53, SP = 1.00, respectively]. After Bonferroni multiple comparisons, a higher GE was perceived in HS than in cycle ergometer exercise (p < 0.001). There were significant differences between M4/S3 vs. all checkpoints in both exercises (p < 0.05). However, a non-significant but sustained decrease was produced from M4/S3 in both exercise modalities (~13%) during constant-load tests (p > 0.05) (FIGURE 5A).

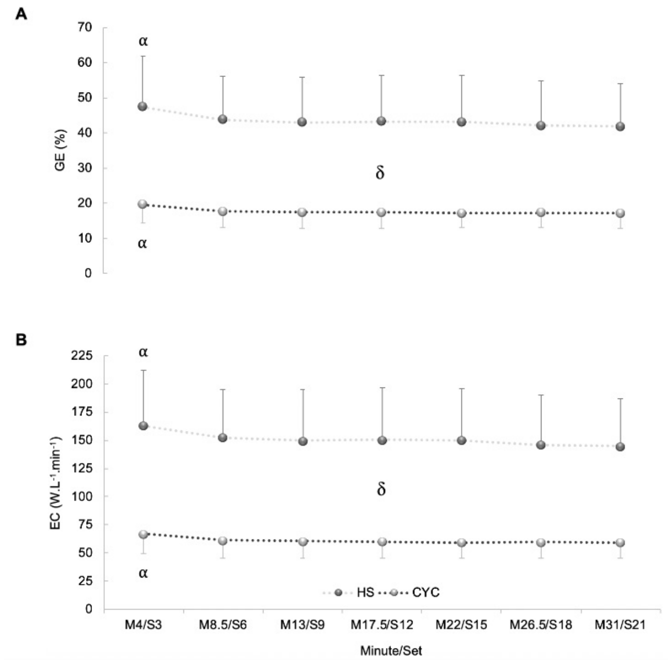

FIGURE 5

Differences between half-squat (HS) exercise and cycle ergometer (CYC) during constant-load test at each checkpoint: (A) Gross efficiency (GE). (B) Economy (EC). α Significantly different from M8.5/S6, M13/S9, M17.5/S12, M22/S15, M26.5/S18, and M31/S21 ($p < 0.05$). δ Significant differences between cycle ergometer and HS exercise at each checkpoint ($p < 0.001$).

In economy, a significant exercise mode x time interaction effect was found [$p = 0.013$, $F_{(6,120)} = 2.85$, η2p= 0.13, SP = 0.88]. A significant exercise mode and time effect was found [$p < 0.001$, $F_{(1,20)} = 61.66$, η2p = 0.76, SP = 1.00; $p < 0.001$, $F_{(6,120)} = 18.84$, η2p = 0.49, SP = 1.00, respectively]. Bonferroni test determined a higher economy in HS than in cycle ergometer exercise ($p < 0.001$). There were significant differences between M4/S3 vs. all checkpoints in both exercises ($p < 0.05$). However, a non-significant but continued decrease was observed from M4/S3 in both exercise modalities ($p > 0.05$) (Figure 5B).

Lower Limbs Fatigue

In CMJ test, a significant exercise mode x time interaction effect was observed in jump height [$p = 0.004$, $F_{(1,20)} = 10.76$, η2p = 0.35, SP = 0.88], mean power [$p = 0.003$, $F_{(1,20)} = 11.82$, η2p = 0.37, SP = 0.91], and peak power [$p < 0.001$, $F_{(1,20)} = 23.61$, η2p = 0.54, SP = 0.99]. In Bonferroni test, significant losses were produced between pre- and post-test in jump height ($p < 0.001$), mean power ($p = 0.001$), and peak power ($p < 0.010$)

only in HS exercise. Peak power was increased after cycle ergometer test ($p < 0.05$) (Figure 6).

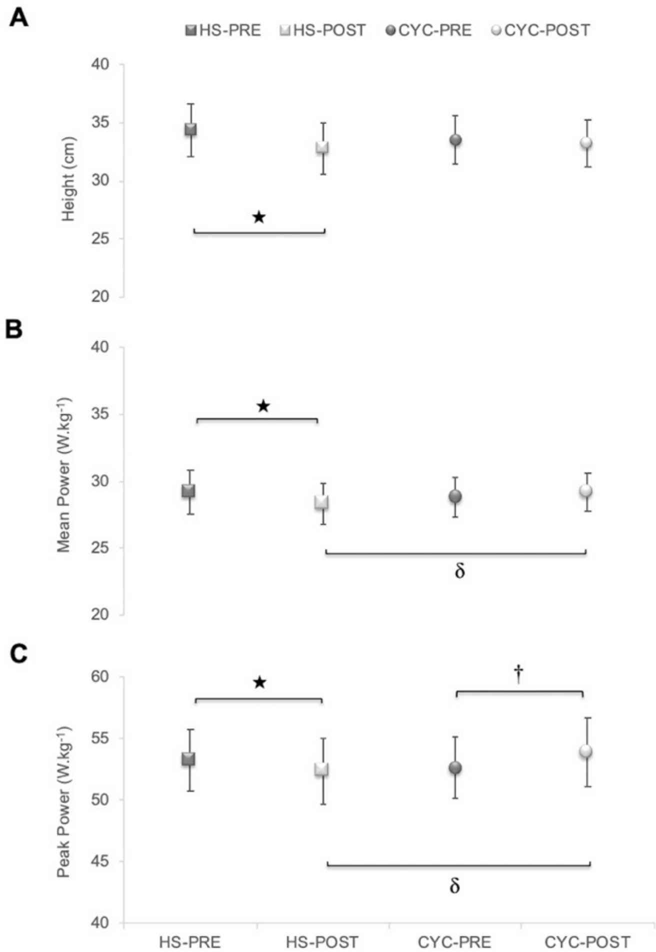

FIGURA 6

Mechanical fatigue evaluated before and after constant-load exercises using a counter-movement jump test. ★Significant differences between pre- and post-test in HS exercise ($p < 0.01$). †Significant differences between pre- and post-test in cycling exercise ($p = 0.011$). δSignificant differences between cycling and HS tests ($p < 0.05$).

DISCUSSION

In support of our initial hypothesis, the main novel finding of this study was that the VO_{2sc} and EE increased slowly only in HS constant-load test at LT_1 intensity. As expected, during cycle-ergometer exercise at a constant work rate, a steady-state in pulmonary VO_2 and EE was reached. These outcomes could justify, at least in part, a decrease observed in jump performance (height and power) only after HS test. Contrary to our expectation, GE/economy in HS exercise did not reduce to a greater magnitude than in cycle ergometer test at the same LT_1 intensity. In addition, there was a higher response in VO_2 and heart rate during the constant-load test in cycle ergometer than in the HS exercise.

The results of VO_{2sc} obtained in HS exercise (absolute values 141.4 mL in 28 min, relative values 5.05 $mL.min^{-1}$) were slightly higher than in the cycling test (absolute values 131.8 mL in 28 min, relative values 4.7 $mL.min^{-1}$). HS results were reinforced by our previous investigations (Garnacho-Castaño et al., 2018a) that found similar VO_{2sc} values in HS exercise (absolute values 153.8 mL in 28 min, relative values 5.49 $mL.min^{-1}$), slightly higher in absolute values (130 mL in 17 min) and slower in relative values (7.6 $mL.min^{-1}$) than that obtained by professional cyclists at intensities clearly above the LT_1 (80% VO_{2max}) (Lucía et al., 2000). These results visibly differed from those reported in well-trained triathletes during constant work rate at 90% of VO_{2max} in cycling (absolute values 269 mL in 10 min 35 s, relative values ~25 $mL.min^{-1}$) and running (absolute values 21 mL in 10 min 54 s, ~2 $mL.min^{-1}$) (Billat et al., 1998). These variances of VO_{2sc} are not fully understood, though they could be related to the difference in the magnitude of VO_{2sc} between exercise modes and load intensity (Carter et al., 2000; Koppo et al., 2002), training status (Burnley and Jones, 2007), and prolonged constant-load tests (Hopker et al., 2017).

The physiological mechanisms that cause the increase of VO_{2sc} during constant-load HS test are uncertain because the power output or load equivalent to the LT_1 intensity means, in theory, the highest power output or load that will not elicit VO_{2sc} (Burnley and Jones, 2007). The VO_2 kinetics observed during constant-load cycling test justified a steady state in VO_2 and EE at the LT_1 intensity. In consequence, the blood lactate increased above the resting values, but did not accumulate over time as occurred during both constant-load tests (Garnacho-Castaño et al., 2015a). If VO_2 continued to increase, especially at the end of the constant-load HS test, it could be assumed that the VO_{2sc} is associated with fatigue and a decrease in muscular efficiency, so blood lactate should accumulate at a constant or increasing rate in response to the transition toward a predominantly anaerobic metabolism (O'Connell et al., 2017). The only hypothesis that was confirmed was an increase in VO_{2sc} and EE linked to lower limbs fatigue at the end of the HS test. Blood lactate was oxidized in a mainly aerobic metabolism and exercise intensity was considered as being at or below the anaerobic or LT (Svedahl and MacIntosh, 2003).

This detected response of VO_{2sc} in HS exercise usually occurs at intensities above the LT_1 in endurance exercises. Unlike the cycle ergometer test, performing 31 min (21 sets) of HS exercise at the LT_1 intensity would only be conceivable with a recovery time between each set. Although break durations of 30 s have indicated negligible effects on lactate kinetics during discontinuous protocols (Gullstrand et al., 1994), our HS protocol caused a relative lack of O_2 supply to muscle loci, further suggesting that an important percentage of the energy derived from anaerobic metabolism might not be quantified by measuring metabolic gas exchange (Garnacho-Castaño et al., 2018a). The HS test probably stimulated a release of anaerobic sources to EE (Tesch et al., 1986) that make it impossible to use steady-state VO_2 to exactly estimate the EE (Scott et al., 2011).

Another feasible mechanism that would help to better understand the etiology of the VO_{2sc} in resistance exercises links the slight increase in pulmonary VO_2 with the VO_2 rise into the muscle. It has been suggested that increased leg VO_2 could explain for ~85% of the rise in pulmonary VO_2 (Poole et al., 1991). Probably, VO_{2sc} discovered in HS exercise increased leg VO_2 within the active muscle to a greater magnitude than in the cycle ergometer test and, consequently, EE was augmented only during HS test. The VO_{2sc} and EE increase would presumably be associated with an increased ATP cost of force production and or increased O_2 cost of ATP resynthesis (Cannon et al., 2014; Korzeniewski and Zoladz, 2015). This energy mechanism would force a delayed recruitment of larger and less efficient motor units from the oxidative point of view to compensate the production of attenuated force in those already active motor units. So, a preferential glycogen depletion of the type I fibers (Vøllestad and Blom, 1985) and the recruitment of type II fibers (Whipp, 1994; Barstow et al., 1996) has been postulated as the most acceptable explanation for the VO_{2sc} (Gaesser and Poole, 1996).

Glycogen depletion patterns have been detected in type I/II fibers, confirming that both fast-twitch glycolytic muscle fibers and slow-twitch oxidative muscle fibers were activated during high intensity cycling exercise at 80% of VO_{2max}. When cycling exercise was performed at moderate intensity (50% of VO_{2max}), only type I fibers were recruited and no VO_{2sc} was observed (Krustrup et al., 2004). These findings suggest the recruitment of type I fibers by this mechanism probably occurred during constant-load cycling test. For this reason, VO_2 was not increased and lower limbs fatigue was not induced at the end of constant-power output cycling. The goal of this study was not to evaluate the gradual fibers-type recruitment associated with the energetic cost; therefore, our arguments are based on findings of others. Nevertheless, it can be assumed that VO_{2sc} and the corresponding increase in EE could be related to progressive fatigue in HS exercise (Garnacho-Castaño et al., 2018a).

In theory, the recruitment forced of type II fibers should induce higher blood lactate concentrations in HS exercise. We suspect that there was no increase in blood lactate levels because a recovery time of 1 min was established between sets. Beneke et al. (2003) demonstrated that repetitive interruptions (90 s after every 5th minute) during 30 min of constant-load testing decreased blood lactate concentrations to a greater extent than without interruptions. During the rest time between sets, the VO_2 of the whole body is still raised as a result of elevated post-exercise VO_2 while the glycolytic rate of the working muscle mass is diminished. Therefore, the rate of lactate removal is directly linked to VO_2 under the saturation conditions of the substrate.

In addition, the RER was similar and remained stable throughout the constant-load tests despite the $VO_2$was higher in the cycle ergometer than HS exercise. The RER during a constant-load test determines the percentage of carbohydrates and fats that are being used as an energy substrate. In endurance exercises have been observed that the fat oxidation is greater during running on treadmill than in the cycle ergometer at the same relative intensity (Achten et al., 2003; Cheneviere et al., 2010). This variance is partly originated by a greater degree of localized intramuscular tension during cycle exercise, which increases the recruitment of fast-twitch motor units (Carter et al., 2000) which mainly depend on carbohydrates as a fuel substrate. As the exercise intensity increases, the change in substrate metabolism toward greater carbohydrates dependence is related to a higher recruitment of the fast-twitch motor units (Coyle, 2000) and the appearance of free fatty acid entrapment (Romijn et al., 1993).

Maybe these physiological mechanisms occurred, at least in part, in the HS exercise. Probably, the HS exercise caused a higher intramuscular tension per muscular unit in the knee extensors than the cycle ergometer, intensified by the negative or eccentric work of the HS exercise. This mechanism might induce a gradual recruitment of less efficient type II muscle fibers as the initially recruited type I fibers become fatigued (Carter et al., 2000). In preliminary tests, we discovered that a recovery time between series equal to or less than 45 s produced an exponential increase in blood lactate levels and relevant muscular fatigue. The rest time of 1 min accumulated between sets throughout the constant-load HS test was a key factor to prevent a greater increase in the carbohydrates and replenish energy substrates and, therefore, for maintaining blood lactate levels in a stable aerobic metabolism.

Although the total time of the tests was the same in both exercises, the real time of execution was 10 min 30 s in HS exercise. The 20 min 30 s of recovery time during HS test could justify, at least in part, that the VO_2 and heart rate was lower in the HS test than cycle ergometer exercise. At the muscular level, probably, the HS exercise was more intense, producing a higher local muscular fatigue. Maybe for this reason, greater fatigue was found in lower limbs after the constant-load HS test. It could be deduced that the muscular fatigue produced in HS exercise stimulated the VO_{2sc} to a greater extent than the cycle ergometer having a higher cardioventilatory response. Despite these physiological mechanisms, the RPE was the same in both exercises.

In order to explain the VO_{2sc} phenomenon, GE was compared in both HS and cycling exercises. GE values in the cycle ergometer test were similar to that obtained by well-trained cyclists (~18%) during long-term constant-load tests at moderate intensity. In HS exercise, we verify our previous findings with GE values of ~44%. Values of ~24–26% have been proposed in professional riders at the power outputs eliciting the LT and the respiratory compensation point during a ramp test (Lucía et al., 2002). Other studies have found lower GE values of 14–16% in world-class sprint cross-country skiers (Sandbakk et al., 2010). These values confirm the idea that GE is conditioned by the exercise modality.

According to results obtained in VO_{2sc} and EE during HS exercise, one could expect to discover a greater GE/economy loss throughout the constant-load HS test. Conversely, a 13% loss (non-significant) in GE was observed in both exercise modalities during constant-load tests. Previous studies have demonstrated that GE continues to diminish during prolonged constant-load tests in cycling (Hopker et al., 2017) and HS exercises (Garnacho-Castaño et al., 2018a) at moderate intensity. We suspect that the higher values and the non-loss of GE throughout the constant-load HS test in comparison with the cycle ergometer test were mainly due to the type of muscular action involved in both exercise modalities. HS execution is characterized by eccentric and concentric muscle actions; cycling prioritizes concentric muscle actions (Ericson et al., 1985). A greater increase in O_2 cost has been shown in no-rebound squats compared to eccentric-concentric squats, and rebound squats stimulate higher efficiency than only concentric squats (Villagra et al., 1993). Pre-stretch allows for storage of elastic energy in the elastic components (muscles and tendons), producing an extra energy that is released during the shortening cycle, probably decreasing O_2 cost. Furthermore, previous studies have demonstrated higher VO_{2sc} in cycling, compared to running (Carter et al., 2000). The authors speculated that the differences between the two exercise modalities were produced by the greater intramuscular tension induced during heavy cycling exercise and the higher eccentric muscle activity in running. This might cause a relatively lower recruitment of the less efficient type II muscle fibers in running (Carter et al., 2000). The pre-stretch could help to prevent a higher VO_{2sc}, decreasing O_2 cost and increasing efficiency in HS exercise to a greater extent than concentric pedaling, avoiding a higher recruitment of type II fibers. Furthermore, the eccentric phase has been demonstrated to be a key factor for improving concentric kinetic/kinematic performance during resistance exercises (Garnacho-Castaño et al., 2018b). Our results demonstrated higher power output levels and a lower VO_2 during constant-load HS exercise than in the cycling test. This increased power output contributed to improve GE in HS exercise. In consequence, variances in power output measures between a cycle ergometer and a linear position transducer should be considered.

We think that the muscle mass involved during exercise is another factor to consider. Several studies have shown a slower VO_{2sc} in running than in cycling (Billat et al., 1998; Carter et al., 2000), or a higher relative increase in VO_2 per unit of time during arm exercise than in a cycling test (Koppo et al., 2002) when a lower muscle mass was involved or when exercise was focused on a specific muscle group. Although the muscle groups involved in HS and cycling exercises are mainly the knee extensors, during HS exercise other muscle groups (i.e., CORE, back, etc.) are likely activated more than in the cycle ergometer exercise. The greater muscle mass involved may help to increase the whole-body efficiency, diminishing O_2 cost.

There are some limitations in this study which should be considered. Eccentric muscle action is linked to significantly higher muscle temperatures than concentric muscle action when both are performed at a comparable power output, rate of oxygen uptake or heat production (Nielsen et al., 1972; Pahud et al., 1980). This fact may *per se* increase the metabolic rate without any other additional perturbations of the muscular milieu. This increased temperature during negative work in HS exercise could have altered the VO_2 kinetics by accelerating the rate-limiting metabolic reaction connected with oxidative phosphorylation and, moreover, accelerating a greater VO_2 delivery to the capillaries and mitochondria (Koga et al., 1997). It would have been interesting to evaluate how it affects the temperature and the positive (concentric) and negative (eccentric) work at the O_2 cost and consequently to the VO_2sc during constant-load tests.

In addition, the different methodology and protocols applied in both exercises during the incremental tests generates some controversy in the location of the LT_1. This factor could condition the cardioventilatory and metabolic responses during the constant-load tests at LT_1 intensity, producing a bias when comparing both exercises. However, the results reported during the incremental test (Table 1) revealed that the detection of the LT_1 in both exercises could occur in an equivalent metabolic instant and a similar exercise intensity. This idea is based on the fact that no significant differences were found in VO_2, heart rate, blood lactate concentrations and RPE between the HS and the cycle ergometer at the LT_1. Our findings are supported by the criteria established in a previous study (Binder et al., 2008). In both exercises, LT_1occurred at a heart rate of ~65–70% of the maximum heart rate, a rating of perceived exertion of ~10 and a blood lactate concentrations of ~2 $mmol.L^{-1}$, which is considered as a light intensity according to the criterion defined at the time of the LT_1.

Although it appears that the LT_1 occurred at a similar metabolic moment and intensity during both incremental tests, the cardioventilatory response during the constant-load test at LT_1 intensity was lower in HS exercise. The controversy is now focused on knowing whether both constant-load protocols occurred at the same relative intensity (% VO_{2max}). To solve this problem, both incremental protocols should have been carried out until exhaustion to determine the VO_{2max} and calculate the percentage of VO_2 in both constant-load tests. The response of blood lactate levels and RPE observed throughout the constant-load test determined, at least, a predominantly aerobic metabolic intensity.

Finally, several studies (Carter et al., 2002; Koppo et al., 2002) have compared the ventilatory responses and the VO_{2sc} between several exercises at the same relative intensity (at, above, below of LT_1). The behavior of VO_2 and VO_{2sc} is exercise- and intensity-dependent despite they are tested at the same relative or metabolic intensity. Resistance training is typically anaerobic in nature. We think that the most important contribution of this study is that resistance exercises might acquire aerobic metabolic properties selecting a suitable load and manipulating the recovery and execution time of the sets.

CONCLUSION

Although the VO_2 and heart rate responses were higher in cycling exercise, the HS constant-load test induced a greater VO_{2sc} and EE than the cycling test at the LT_1 intensity. GE could benefit from the eccentric phase of the HS exercise. Resistance training conducted at a load intensity equivalent to a predominantly aerobic metabolism could improve local muscular resistance and whole-body efficiency. Thus, relevant implications for both performance and health exercise programs could be considered. This would allow a faster recovery of the muscle groups from one session to another. In the fitness programs, this methodology would help complement the aerobic endurance training with resistance exercises that involve a greater muscle mass (CORE, upper limbs, stabilizers, etc.) and a higher mechanical efficiency in a metabolism that is primarily aerobic. Future research should focus on continuous protocols (without rest periods) as in endurance exercise, combining resistance exercises in the form of circuit training. This scientific knowledge could be an important advance in the assessment of resistance exercises for sports performance and health promotion.

DATA AVAILABILITY

All datasets generated for this study are included in the manuscript and/or the supplementary files.

AUTHOR CONTRIBUTIONS

JM-M and MG-C conceived and designed the research. All authors performed the test protocols and edited, revised, and approved the final version of the article. MG-C and JM-M analyzed the data. LA-A, NS-P, MB, RF-R, LC, and EC contributed reagents, materials, and analysis tools. LA-A, JM-M, RF-R, and MG-C prepared the figures and drafted the article.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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9. ARTÍCULO 3

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Ventilatory efficiency during constant-load test at lactate threshold intensity: Endurance versus resistance exercises.

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ABSTRACT

There is a lack of evidence about the ventilatory efficiency in resistance exercises despite the key role played in endurance exercises. This study aimed to compare the cardiorespiratory, metabolic responses and ventilatory efficiency between half-squat (HS) and cycle ergometer exercises during a constant-load test at the lactate threshold (LT) intensity. Eighteen healthy male participants were randomly assigned in a crossover design to carry out HS or cycle ergometer tests. For the three HS tests, a one repetition maximum (1RM) test was performed first to determine the load (kg) corresponding to the 1RM percentages. In the second test, the incremental HS exercise was carried out to establish the load (kg) at the LT intensity. Finally, a constant-load HS test was performed at the LT intensity. The first cycle ergometer test was incremental loading to determine the intensity in watts corresponding to the LT, followed by a constant-load test at the LT intensity. A recovery time of 48 hours between each test was established. During both constant-load test, cardiorespiratory and metabolic responses were monitored. A significant exercise mode x time interaction effect was only detected in oxygen uptake (VO_2), heart rate, and blood lactate ($p < 0.001$). No differences were found between the two types of exercise in ventilatory efficiency ($p > 0.05$). Ventilation (VE) and carbon dioxide were highly correlated ($p < 0.001$) in the cycle ergometer ($r = 0.892$) and HS ($r = 0.915$) exercises. In the VO_2 efficiency slope (OUES), similarly significant and high correlations ($p < 0.001$) were found between VO_2 and $\log_{10}$ VE in the cycle ergometer ($r = 0.875$) and in the HS ($r = 0.853$) exercise. Although the cardioventilatory responses were greater in the cycle ergometer test as compared to HS exercise, ventilatory efficiency was very similar between the two exercise modalities in a predominantly aerobic metabolism.

INTRODUCTION

Recent studies have used the lactate threshold (LT) or the ventilatory threshold as parameters to monitor and assess cardiorespiratory responses [1, 2, 3], slow component of oxygen uptake, and gross mechanical efficiency [4] in unusual resistance exercises using a cardiopulmonary exercise tests (CPET), as also occurs in endurance exercise [5-9]. During constant-load test at a load intensity equivalent to the LT, it was observed a greater cardiorespiratory response to cycle ergometer exercise compared to the half-squat (HS). The cardiorespiratory and metabolic response was stable in both types of exercise; greater muscular fatigue was observed after completion of the HS test [2]. As could be expected, resistance exercises increased local muscular fatigue in the lower limbs, while endurance exercises increased cardiorespiratory response.

Cardiorespiratory fitness is frequently evaluated by means of ventilatory efficiency [10, 11]. The fundamental cause of ventilatory efficiency is the matching of ventilation (VE) and perfusion in the lungs. The mismatching of perfusion and VE diminishes the efficiency of lung gas exchange, demanding an increase in VE for a given CO_2 output and arterial PCO_2. This mismatching phenomenon contributes essentially to hyperpnea and dyspnea [12] affecting ventilatory performance. It is common to assess ventilatory efficiency in endurance exercises mostly in different types of diseases or pathologies [13-14], in sports performance [11], and in healthy subjects [10, 15], establishing the slope of the linear relationship between VE and carbon dioxide (VE/VCO_2 slope) during an incremental test up to the anaerobic [16] or ventilatory threshold [17] and the ventilatory compensation point [10]. Another option to quantify ventilatory efficiency in endurance exercises is to determine the oxygen uptake efficiency slope (OUES). The OUES indicates how effectively oxygen is extracted and taken into the body during incremental exercise [17]. The OUES is considered a very appropriate tool in the evaluation of cardiovascular fitness in overweight adolescents [18], the severity of heart disease [19], the effects of physical training or treatment [20, 21], and the risk of a serious or fatal event [22].

Although many studies have analyzed the slope of VE/VCO_2 and OUES by age, sex, fitness level, and diseases in endurance exercises [10, 11, 14, 17, 19], it is unusual to observe studies comparing VE/VCO_2 slope and OUES between different exercise modalities [23, 24]. Sun et al. [10] demonstrated that VE/VCO_2 slope is not exercise mode-dependent, however, Davis et al. detected that VE/VCO_2 slope was lower on the cycle ergometer than the treadmill in women but not in men [25]. For OUES, treadmill values were higher than cycle ergometer [24]. Recently, Salazar-Martinez et al. demonstrated that ventilatory efficiency was unaffected by ergometer type [26]. The assumption that ventilatory efficiency could be similar between different exercise modalities is controversial and more research is needed to compare several exercise modes. Despite the importance that has been given in the scientific literature to the assessment of ventilatory efficiency in endurance exercises in healthy people and especially in the clinical settings, it is a field of knowledge that needs to be explored in resistance exercises. There are no previous data regarding VE/VCO_2 slope and OUES in HS exercise and, to the best of our knowledge, ventilatory efficiency has not been compared between resistance and endurance exercises.

In cardiorespiratory fitness assessment, this knowledge could have an added value in selecting the type of exercise to improve ventilation efficiency. If resistance exercises demonstrate adequate ventilatory efficiency, professionals in the health field could use resistance training to increase local muscle endurance while maintaining good ventilatory efficiency.

It is common to assess ventilatory efficiency during incremental endurance tests, however, prolonged constant-load endurance tests can be recommended as a good option in the clinical health setting to determine the VE/VCO_2 slope [27, 28] or OUES because they do not subject the participants to significant cardiorespiratory, metabolic, and muscular stress. A constant-load test at LT intensity might be an interesting alternative for applying to healthy people in both endurance and resistance exercises to assess ventilatory efficiency without inducing a strenuous cardiorespiratory and metabolic stress.

The main objective of this study was to compare the ventilatory efficiency, measured by OUES and VE/VCO_2 slope, and cardioventilatory responses of HS and cycle ergometer exercise in a constant-load test at LT intensity. A secondary goal was to determine the relationship between the OUES and the VE/VCO_2 slope in both exercise modalities in each participant.

MATERIAL AND METHODS

Participants

Eighteen healthy male participants were recruited among the students of the Department of Physical Activity and Sports Sciences (age: 21.8 ± 1.5 years, height: 180.3 ± 5.7 cm, weight: 82.6 ± 9.0 kg, body mass index: 25.4 ± 2.0). All participants had at least 6 months of resistance training experience and were completely familiar with the HS exercise and the cycle ergometer.

Four exclusion criteria were established: 1) any cardiovascular, metabolic, neurological, pulmonary, or orthopedic disorder that could limit exercise performance, 2) the use of any medication, supplements, or substance that could improve performance, 3) 1RM ≤150 kg in the exercise of the HS, 4) elite athlete status.

Eligible participants were informed of the tests to be performed and those who agreed with the study protocols signed their written consent to participate. The subjects were instructed to abstain from other exercise or training during the two-week study period. The study protocol adhered to the principles of the Declaration of Helsinki for studies with human beings and was approved by the Ethics Committee of the Alfonso X El Sabio University (Villanueva de la Cañada, Madrid, Spain).

Experimental design

The participants visited the Exercise Physiology Laboratory five times during the two-week study period, at the same time of day (± 2 hours) and in similar environmental conditions (room temperature 21-25 ºC, atmospheric pressure 715-730 mm Hg, relative humidity ~ 45%). Participants were randomly assigned in a crossover design to perform HS or cycle ergometer tests. A rest period of 48 hours was established between each of the five tests. The protocols were implemented according to procedures previously established by our research group [2].

For the three HS tests, a one repetition maximum (1RM) test was performed first to determine the load (kg) corresponding to the 1RM percentages to be used during the second test, the incremental HS exercise to establish the load (kg) at the intensity corresponding to the LT. Finally, a constant-load HS test was performed at the LT intensity established during the incremental exercise test. The first cycle ergometer test was incremental loading to determine the intensity in watts (W) corresponding to the LT, followed by a constant load test at the LT intensity. During both constant-load test, acute cardiorespiratory and metabolic responses were monitored. The timing of the blood lactate sampling was the same for both the HS and cycle ergometer testing.

Half squat tests

In the HS tests, a Smith machine (Matrix Fitness, Johnson Health Tech, Cottage Grove, MN, USA) was used to ensure safe and controlled movements. HS technique was determined as in previous studies [3, 29]. The variation in range of motion (ROM) during HS exercise was accurately determined during a familiarization session and in all the tests. Participants positioned themselves under the barbell in an upright position with the knees and hips fully extended and legs spread approximately at the shoulders' width. The barbell was placed on the upper back (trapezius muscle), approximately at the level of the acromion. During the descent of the bar, participants flexed the knees and hips (eccentric action) to lower the barbell in a controlled manner, until 90^0 flexion of the knees [30]. From this position, the concentric muscle action was started until fully extending the knees and hips. The body position was individually adjusted and exactly replicated on each HS test.

Each HS test started with a 5-minute low-intensity general run and 5-minute general joint mobility warm-up, followed by a specific warm-up of a series of 3-5 repetitions (HS) at a relative intensity of 40-60% of 1RM.

1RM test

After a 2-minute rest, the HS test protocols began. To determine 1RM, 3-5 series were carried out, using an increasing weight each time. The 1RM was defined as the last load lifted by the subject, completing a knee extension to the required position. The rest period between each attempt was 4 minutes.

Incremental HS test

The incremental HS test was carried out in 6 one-minute series, at relative intensities of 10%, 20%, 25%, 30%, 35%, and 40% 1RM as described in previous studies [2, 4, 29]. In each series, 30 repetitions of 2 seconds each were performed (1 second for eccentric muscle action and 1 second for concentric action), using a metronome to establish the rhythm; a member of the research team provided visual and verbal cues to maintain an adequate rate. A passive rest period of 2 minutes between series was established. During this period, blood samples were collected by an experienced researcher and the corresponding load was increased. The test ended when the repetitions were no longer executed correctly or was voluntarily terminated by the participant when he could not perform the repetitions at the established cadence. Blood samples (5 µL) were obtained by pricking the finger 30 seconds after the end of each series. Lactate levels were measured using a portable analyzer (Lactate Pro LT-1710, Arkray Factory Inc., KDK Corporation, Siga, Japan).

Based on the algorithmic adjustment method described by Orr et al. [31], LT was defined as the load intensity at which blood lactate concentrations begin to increase exponentially [32]. LT was detected by two-segment linear regression, placing the 2 emergent linear regression equations for each segment at the point of intersection between a plot of blood lactate concentration and relative intensity [33]. Data analysis was done using Matlab version 7.4 (MathWorks, Natick, MA, USA).

Constant-load HS test

In the constant load HS test, 21 sets of 15 repetitions were performed. The duration of each set was 30 seconds (1 second each for the eccentric and concentric phases, guided by a metronome and visual and verbal signals), with 1-minute rest between sets. The entire constant-load test lasted 31 minutes. Respiratory exchange data were recorded during the constant-load test using a breath-by-breath open-loop gas analyzer (Vmax spectra 29, Sensormedics Corp., Yorba Linda, California, USA), previously calibrated. VO_2, VE, VCO_2, and respiratory exchange ratio (RER) were monitored. The heart rate was quantified every 5 seconds by telemetry (RS-800CX, Polar Electro OY, Finland). To determine lactate concentrations, finger-prick blood samples were obtained, as described for the incremental test, at rest and 30 seconds after the end of 7 HS sets (S): S3, S6, S9, S12, S15, S18 and S21.

Cycle ergometer tests

The incremental and constant-load tests on a cycle ergometer (Monark ergomedic 828E, Vansbro, Sweden) included a 5-minute warm-up at a pedaling rate of 50 rev.

min^{-1} and a load of 50 W, followed by 5 minutes of dynamic joint mobility and stretching exercises. The load during the incremental and constant-load tests was defined according to the characteristics of the cycle ergometer, as previously described [34]. Briefly, pedaling at an intensity of 50 W is the same as pedaling at a rate of 50 $rev.min^{-1}$ at a load of 1-kilogram force (kgf). To increase the load by 25 W during an incremental protocol, pedaling cadence at a rate of 50 $rev.min^{-1}$ should be performed at a load equivalent to 0.5 kfg. After 2 minutes of rest, the specific tests on the cycle ergometer began.

Incremental cycle ergometer test

The incremental test using a ramp protocol that started with a load of 50 W (50 $rev.min^{-1}$ at a load of 1kgf), increased in steps of 25 $W.min^{-1}$ until completion of 8 min at a pedaling rate of 50 $rev.min^{-1}$ at a load of 0.5 kgf. Blood samples (5 µL) were obtained by finger pricking at rest and every 2 minutes during the incremental test. The LT was detected by inspecting the plot of blood lactate concentrations against the workload, according to the protocol described by Weltman et al. [35]. LT was defined as the highest exercise load completed when an increase of 0.5 $mmol.L^{-1}$ was detected over baseline concentrations in at least 2 consecutive samples.

Constant-load cycle ergometer test

The constant load cycle ergometer test was performed with continuous pedaling at a rate between 70-80 $rev.min^{-1}$ at an intensity (W) equivalent to the LT, previously determined in the incremental test. The load in kfg was individually adjusted to each subject at 70-80 $rev.min^{-1}$ to develop the W corresponding to the LT intensity. Total duration of the test was 31 minutes. The blood lactate samples were obtained with the same portable analyzer as in the HS test, at the beginning of the test and (coinciding with the timing in the HS test) at the following minutes (M) thereafter: M4, M8.5, M13, M17.5, M22, M26.5, M31. During the constant-load test, respiratory exchange and heart rate data were recorded as described in the HS constant-load test.

Ventilatory efficiency

The ventilatory efficiency of each participant was determined in two ways: 1) the slope of the relationship between VE and VCO_2 during each constant-load test; 2) the OUES slope, calculated as the relationship between VO_2 and the logarithm of the VE during the constant-load test: VO_2 = a log10 VE + b).

Statistical analysis

The Shapiro-Wilk test was used to verify the normal distribution of the data, reported as mean, standard deviation (SD), and confidence intervals (95% CI). To identify significant differences between the HS and cycle ergometer exercises in the cardioventilatory and lactate variables, a general linear model was performed with a two-way analysis of variance (ANOVA) for repeated measurements. The two factors were the exercise mode (HS or cycle ergometer) and time point (corresponding to 7 control points in both exercise modes). When appropriate, a post-hoc Bonferroni adjustment was implemented for multiple comparisons. To determine the differences between the two exercise modes in the VE/VCO_2 and OUES slopes, Student-t was applied for related samples. The slope of VE/VCO_2 and OUES was calculated by linear regression between VE and VCO_2 and between VO_2 and log10 VE, respectively. The Pearson product-moment correlation coefficients were calculated to determine significant relationships between the VE and the VCO_2 and between the VO_2 and the log10 VE, and to establish the possible relationship between the OUES and the VE/VCO_2 slope.

Partial eta square (η_p^2) was calculated to determine the magnitude of the response in ANOVA analysis. Cohen´s *d* for the planned comparisons was used to determine effect sizes. A large effect size was defined as $\eta_p^2 \geq 0.26$, $d \geq 0.80$; moderate $\eta_p^2 \geq 0.13$, $d \geq 0.40$; and small $\eta_p^2 < 0.02$, $d < 0.40$ [36]. Statistical power (SP) was also determined. The intraclass correlation coefficients and the percentage of variation coefficients were calculated to determine the relative and absolute reliability. The level of significance was set at $p < 0.05$. All statistical methods were performed using the SPSS Statistics software package version 23.0 for Macintosh (SPSS, Chicago, IL, USA). The graphics were made in the Microsoft Excel version 16.20 for Mac.

Results

Anthropometric characteristics and incremental test data for the HS and cycle ergometer exercises are shown in Table 1.

Table 1. Descriptive data related to anthropometric characteristics, 1RM- and incremental-load tests

Variables	Mean (SD)
Participants	N = 18
Age (years)	21.17 (1.50)
Height (cm)	180.28 (5.68)
Weight (kg)	82.63 (8.99)
BMI (kg.m^2)	25.39 (2.05)
IRM in HS (kg)	206.28 (36.35)
HS load at LT (kg)	51.20 (9.02)
HS relative intensity at LT (%)	625.79 (4.61)
CYC load at LT (W)	130.83 (24.75).

Abbreviations: 1RM = one-repetition maximum; BMI: body mass index; CYC: cycle-ergometer; HS = half-squat; LT = lactate threshold; SD = standard deviation.

Differences in cardioventilatory and lactate responses are shown in Table 2. The mean of the intraclass correlation coefficients and the coefficients of variation for cardioventilatory variables and lactate were 0.970 (0.942-0.987) and 6.7% ± 3.4%, respectively.

Table 2. Differences in cardioventilatory and lactate responses between half-squat vs cycle-ergometer during constant-load test at lactate threshold intensity

	CYC (95% CI)	HS (95% CI)	*P*[1] ES/SP	*P*[2] ES/SP	*P*[3] ES/SP
VO_2 ($L.min^{-1}$)	2.24	1.62	**0.007**	**< 0.001**	**< 0.001**
	(2.02-2.46)	(1.52-1.71)	0.16/0.91	0.56/1.00	0.64/0.99
VCO_2 ($L.min^{-1}$)	2.05	1.50	**< 0.001**	**< 0.001**	**< 0.001**
	(0.92-0.95)	(1.40-1.60)	0.11/0.73	0.61/1.00	0.62/0.99
VE ($L.min^{-1}$)	53.69	43.08	0.510	**< 0.001**	**0.002**
	(48.15-59.22)	(40.07-46.09)	0.05/0.34	0.43/1.00	0.45/0.94
RER	0.91	0.94	0.923	**< 0.001**	0.084
	(0.90-0.93)	(0.92-0.96)	(0.02-0.14)	(0.48-1.00)	(0.17-0.41)
HR ($beat.min^{-1}$)	139.60	123.75	**< 0.001**	**< 0.001**	**0.001**
	(131.18-148.03)	(116.67-130.83)	0.26/0.1.00	0.61/1.00	0.56/0.99
Lactate ($mmol.L^{-1}$)	2.55	2.84	**< 0.001**	**< 0.001**	**0.148**
	(2.19-2.90)	(2.58-3.09)	0.29/1.00	0.77/1.00	0.12/0.30

Abbreviations used: CYC: cycle-ergometer; ES: effect size; HR: heart rate; HS: half-squat; L: liter; min: minute; RER: respiratory exchange ratio; SP: statistical power; VCO_2: carbon dioxide production; VE: minute ventilation; $VE.VCO_2^{-1}$: ventilatory equivalent for carbon dioxide; $VE.VO_2^{-1}$: ventilatory equivalent for oxygen; VO_2: oxygen uptake. P[1] Significant differences for exercise mode x time interaction effect. P[2] Significant differences for time effect. P[3] Significant differences for exercise mode effect. Data are provided as mean and 95% confidence intervals (95% CI).

For absolute VO_2, a significant exercise mode x time interaction effect was observed ($p = 0.007$, $F_{(6, 102)} = 3.18$). Bonferroni test confirmed that VO_2 was significantly higher in cycle ergometer than HS exercise at the 7 established control points ($p < 0.001$; large effect $d \geq 1.64$). In cycle ergometer, a significant lower VO_2 was detected in M4 regarding the rest of the control points ($p \leq 0.002$; moderate effect $d \geq 0.46$ and ≤ 0.60). However, a VO_2 stabilization was observed after M8.5 ($p > 0.05$). In HS exercise, a significant increase in VO_2 was observed ($p < 0.05$) in S3 with respect to S6 (moderate effect, $d = 0.46$), S18 (large effect, $d = 0.95$), and S21 (large effect, $d = 0.86$) (Fig 1A).

No significant exercise mode x time interaction effect was found for the relative VO_2 ($p > 0.05$) and VE variable ($p > 0.05$).

For heart rate, a significant effect (p <0.001) was observed for exercise mode x time interaction ($F_{(6, 102)}$ = 5.85). The Bonferroni test determined that heart rate was significantly lower in HS exercise than in cycle ergometer test at the 7 established control points (p <0.05; in M4/S3, moderate effect *d* = 0.49; rest of control points large effect *d* ≥ 0.94). In cycle ergometer exercise, a significant increase in heart rate was confirmed in M4 regarding all control points (p < 0.01; moderate effect versus M8.5 and M13, *d* ≥ 0.62 and ≤ 0.74; large effect versus M17.5, M22, M26.5, M31, *d* ≥ 0.83) (Fig 1B).

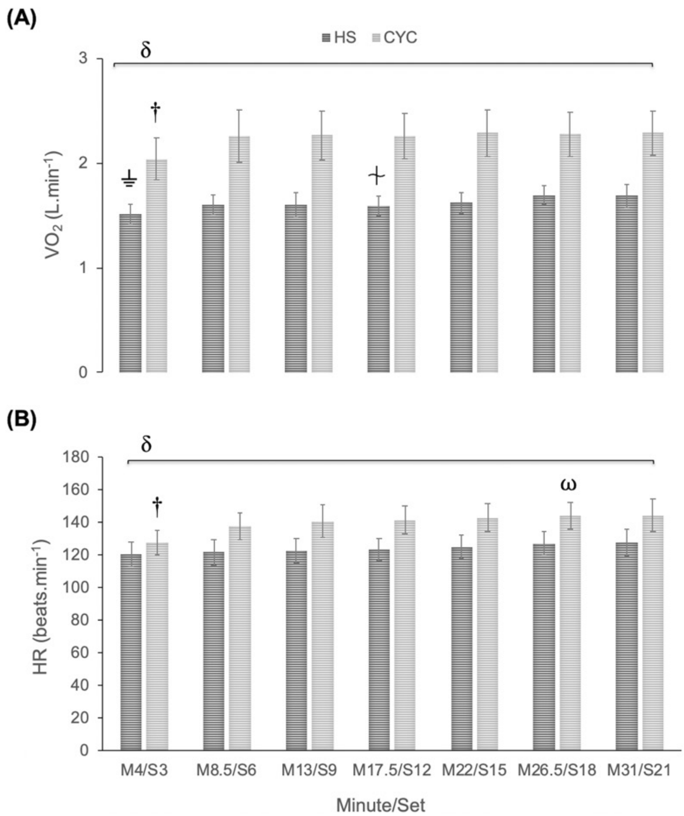

Fig 1. Multiple comparisons between cycle ergometer (CYC) and half-squat (HS): (A) Oxygen uptake (VO_2). (B) Heart rate (HR). δ Significant differences p < 0.05 between cycle ergometer and half-squat at each checkpoint. † Significantly different from M8.5, M13, M17.5, M22, M26.5, M31 in cycle ergometer, p < 0.01. ω Significantly different from M8.5, M17.5 in cycle ergometer, p = 0.017. ⏚ Significantly different from S6, S18, S21 in HS exercise, p < 0.05. ┼ Significantly different from S21 in HS exercise, p = 0.026.

Blood lactate concentrations indicated a significant exercise mode x time interaction (p < 0.001, $F_{(7, 119)}$ = 6.93). The Bonferroni adjustments showed a significant increase from rest period in both exercise modes (p ≤0.005; large effect *d* ≥ 1.71). Significant higher blood lactate levels were found in HS exercise regarding cycle ergometer (p <0.05) at control points M22/S15 (moderate effect, *d* = 0.72), M26.5/S18 (large effect, *d* = 0.82), and M31/S21 (large effect, *d* = 1.19) (Fig 2).

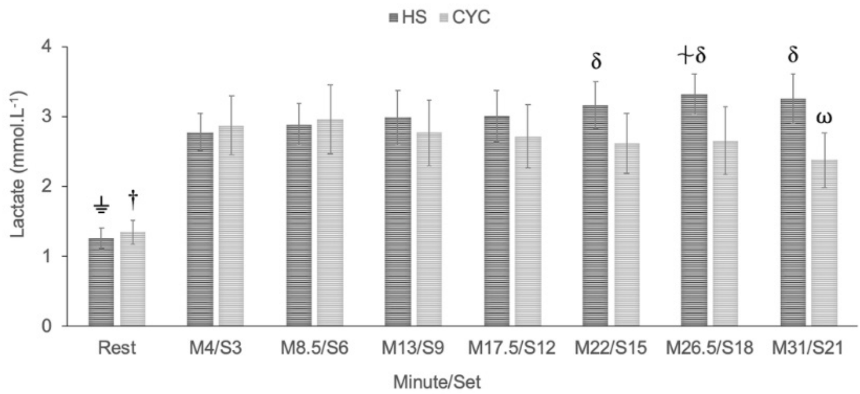

Fig 2. Multiple comparisons between cycle ergometer (CYC) and half-squat (HS) in blood lactate. ⏚ Significantly different from S3, S6, S9, S12, S15, S18, S21 in HS exercise, $p < 0.001$. † Significantly different from M4, M8.5, M13, M17.5, M22, M26.5, M31 in cycle ergometer, $p < 0.01$. δ Significantly different from cycle ergometer in M22/S15, M26.5/S18, M31/S21, $p < 0.05$. ω Significantly different from M4 in cycle ergometer, $p = 0.028$. ┼ Significantly different from S3 and S6 in HS exercise, $p < 0.05$.

In the RER, no significant interaction effect was observed for exercise mode x time ($p > 0.05$).

Regarding VE/VCO_2 slope and OUES, no differences were found between the two types of exercise ($p > 0.05$) (Fig 3).

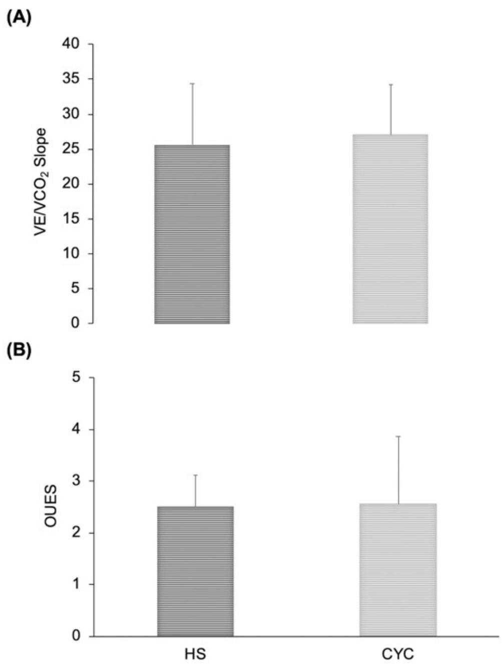

Fig 3. Differences between cycle ergometer (CYC) and half-squat (HS) in the VE/VCO_2 slope and OUES. No significant differences between both exercise modalities

In the VE/VCO_2 slope, VE and VCO_2 were highly correlated ($p < 0.001$), both in the cycle ergometer ($r = 0.892$) and HS ($r = 0.915$) modalities (Figs 4A and 4B, respectively).

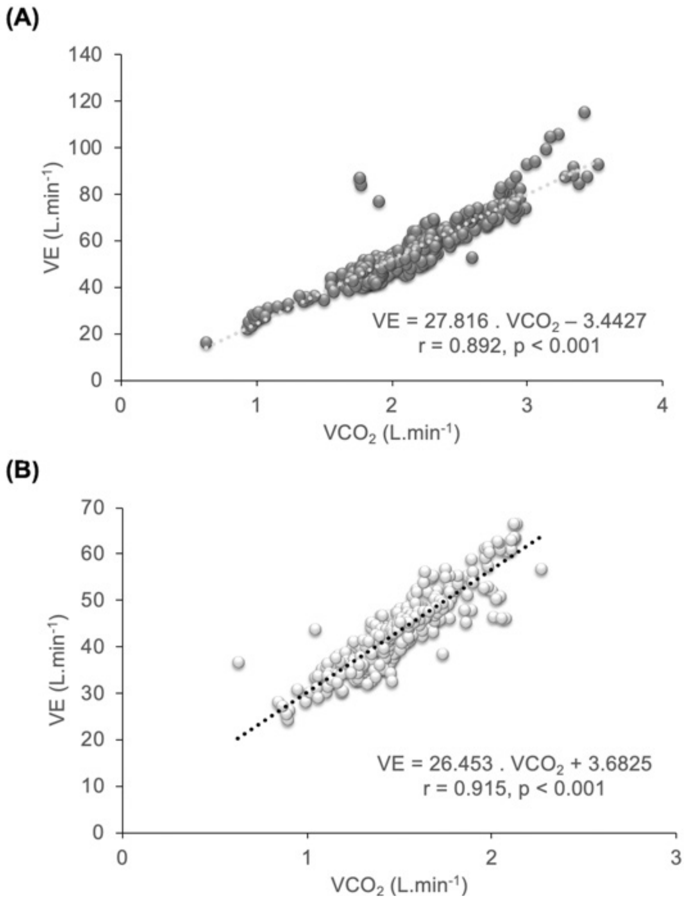

Fig 4. Linear relationship between ventilation (VE) and carbon dioxide (VE/VCO2 slope): (A) Cycle ergometer (CYC). (B) Half-squat (HS).

In the OUES, similarly high correlations ($p < 0.001$) were found between VO_2 and $\log_{10}$ VE in the cycle ergometer ($r = 0.875$) and in the HS ($r = 0.853$) (Figs 5A and 5B, respectively).

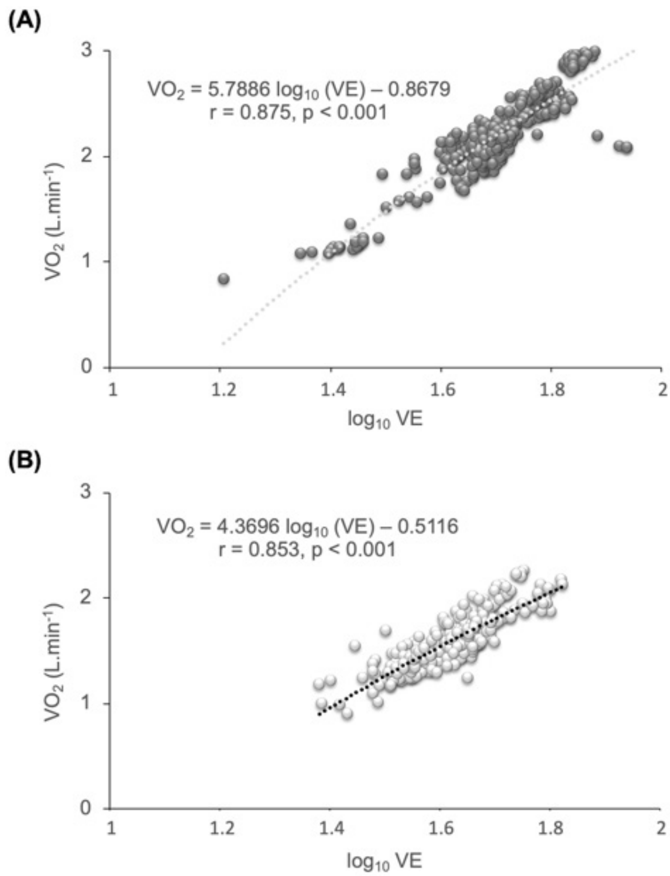

Fig 5. Relationship between oxygen uptake (VO_2) and log_{10} VE (OUES): (A) Cycle ergometer (CYC). (B) Half-squat (HS).

No significant correlation was found between the OUES and the slope of the VE/VCO_2 in the HS ($r = -0.345$, $p = 0.160$) nor in the cycle ergometer ($r = 0.315$, $p = 0.203$). Also, no significant correlation was observed between the HS and cycle ergometer modes in OUES ($r = 0.356$, $p = 0.147$) or VE/VCO_2 slope ($r = 0.422$, $p = 0.081$).

DISCUSSION

To the best of our knowledge, this study applied two novelties in methodological approach, with respect to previous research. First, it determined ventilatory efficiency in HS exercise by two distinct methods (VE/VCO_2 slope and OUES); second, it compared HS and cycle ergometer ventilatory efficiency in constant-load tests conducted at an intensity equivalent to the LT. Although the cardioventilatory responses were greater in the cycle ergometer test as compared to HS, ventilatory efficiency was very similar between the two exercise modalities. In addition, the blood lactate concentrations were similar between both exercise modes although these values were slightly higher in HS exercise than in the cycle ergometer exercise at the end of the constant-load tests.

These findings replicated the results obtained in previous investigations, in which the cardiorespiratory responses were higher in the cycle ergometer test than in HS exercise [2]. The constant-load HS test at LT intensity likely induced a lower cardioventilatory response because a rest time was implemented between sets. To date, it has been unfeasible to perform a continuous protocol in the HS exercise at the LT intensity. In theory, a continuous HS protocol would increase intramuscular pressure leading to augmented muscle tension and progressive fatigue. These physiological mechanisms would produce the collapse of capillaries and diminish the oxygen available into the muscle and thus increasing the blood lactate levels [37]. Although it is usual to find a different cardiorespiratory response between several endurance exercise modalities at the same relative intensity [38], the available studies comparing resistance versus endurance exercises during constant-load test at LT intensity are currently insufficient to draw more precise conclusions.

The VE/VCO_2 slope and OUES results obtained in both exercises are considered normal and comparable to other studies with healthy adults (19-30 in VE/VCO_2 slope, 2.55 ± 1.01 n = 417 in OUES) [10, 16, 24]. In elite youth cyclists [11], the slope of the VE/VCO_2 was similar (about 28) to our study, but the OUES was higher: 3.8 vs. 2.5 in our study. The difference could be due to the novel methodology used in our study and the greater cardiorespiratory fitness of elite youth cyclists. No studies are available for comparison of the VE/VCO_2 slope, cycle ergometer values, or HS data in a constant-load test at LT intensity. However, our results on ventilatory efficiency were very similar to those obtained in other studies in endurance exercises (cycling) at the intensity of the anaerobic threshold [11], perhaps because both intensities (LT and anaerobic thresholds) reflect a similar metabolic moment, beyond which lactate concentrations begin to increase. Our data from both exercise modes in healthy young adults verify that this protocol could be another option to evaluate the slope of VE/VCO_2 and OUES in a mostly aerobic metabolism, controlling the acidosis of the body, without having to reach the high intensities and avoiding a higher cardiorespiratory stress that could become problematic in some pathologies. Probably, during a constant-load test at moderate intensity (LT) the relationship between VE and both VCO_2 and VO_2 is normally stable and uniform before the onset of ventilatory compensation for the exercise-induced lactic acidosis [10], justifying, at least in part, the similarities detected in VE/VCO_2 slope and OUES between both exercise modalities at the same metabolic state.

A surprising aspect of this study was the almost identical values in the ventilatory efficiency observed in the HS and cycle ergometer tests. Studies comparing the VE/VCO_2 slope and the OUES in different types of exercises are rare; therefore, there is a significant lack of information about which exercise modality could induce a higher ventilatory efficiency. Our findings show that two types of exercise with different cardioventilatory responses induce the same ventilatory efficiency at similar metabolic intensity. During incremental exercise tests [23], no significant changes were found between treadmill and cycle ergometer trials, although both exercise modalities showed a lower VE/VCO_2 slope (higher efficiency) compared to a robotics-assisted tilt table. A study compared OUES in 17 healthy subjects in two exercise modalities, observing higher values in the treadmill test compared to the cycle ergometer [24]. Although further evidence is needed, ventilatory efficiency could be dependent on the type of exercise, test protocol, and mode of assessing ventilatory efficiency (OUES vs VE/VCO_2 slope).

It was expected that subjects with a lower VE/VCO_2 slope (greater efficiency) throughout each of the tests would increase their OUES. The lack of significant correlation between the OUES and the slope of the VE/VCO_2 in the two exercise modalities analyzed indicates that those subjects who showed greater ventilatory efficiency in the HS did not achieve greater ventilatory efficiency in the cycle ergometer. The OUES has been accepted as a valid submaximal measure of the function and prognosis of disease [39], and the slope of VE/VCO_2 is a reliable assessment in healthy adults [40] and in those with pathologies [41]. However, their usefulness in healthy and athletically trained people is dubious. It is not yet clear which factors contribute to modify ventilatory efficiency during exercise, but the established postulates through this discussion may be more relevant in the clinical field than in fitness and sports performance because it seems that the VE/VCO_2 slope did not change in elite cyclists after 16 weeks of training [11] and, regardless of gender, in children [42] and healthy adults [10] engaging in exercise. Training did not improve the OUES in healthy subjects [43] and could have a limited effect in athletes [11].

As a practical application, these findings could be an interesting alternative for the processes of physical rehabilitation and recovery from diseases associated with a loss of strength and muscle mass. For example, patients with heart failure are characterized by a significant loss of muscle mass, and these same physiological mechanisms are closely related to dyspnea and ventilatory fatigue [44]. Therefore, ventilatory efficiency is related to the severity of heart failure with reduced ejection fraction [45, 46] and, as a corollary, poor ventilatory efficiency is related to increased morbidity and mortality. In addition, it is common to diagnose strength and muscle loss (sarcopenia) in older adults. Sarcopenia is a prevalent syndrome associated with premature mortality in elderly [47]. Resistance exercises at LT intensity could increase local muscular endurance avoiding the losses of strength and muscular mass and, in addition, with the same ventilatory efficiency that could produce the cycle ergometer exercise. Unfortunately, our arguments cannot be consolidated with previous studies in different pathologies, as data clarifying the effect of the resistance exercises to LT intensity in patients with heart failure or sarcopenia are not available; therefore, these observations remain purely intuitive and speculative. It is clear that the combination of both resistance and endurance training has improved exercise capacity and diastolic function in patients with heart failure with reduced ejection fraction [48]. Accordingly, the combination of resistance exercises and endurance exercises could be an adequate methodology to increase cardiorespiratory response (endurance exercises) on the one hand and strength and muscular resistance (resistance exercises) on the other hand.

There are some limitations in this study with regard to the HS exercise protocol, which should be considered. The experimental procedures established in both incremental tests prompt controversial debate with regards to the location of the LT. Consequently, the relative intensity or external load prescribed in each exercise could have been different during both constant-load tests. In this case, an important bias would occur when comparing ventilatory efficiency, cardiorespiratory and metabolic responses between both exercises. However, the results reported by our research group in a recent study [49] revealed that the detection of the LT in both exercises using this same methodology could occur at a similar metabolic instant and relative intensity according to the criteria defined by Binder et al. [50]. In both incremental tests, an equivalent load intensity was produced at the LT, however, cardiorespiratory response was higher in cycle ergometer than in HS exercise during constant-load tests. It is habitual to observe an unequal cardioventilatory response when several exercise modes are compared at the same relative intensity or external load [51]. An identical trend was found in other studies that compared blood lactate, RER and cardiorespiratory responses in various exercises at lower and moderate intensities [38, 52]. Probably, cardiorespiratory responses are exercise mode-dependent at the same metabolic intensity and, therefore, these differences seem larger and more important to considerer at lighter and moderate intensities [38].

We cannot fail to mention that the recovery time established between each series is a key factor in maintaining low and stable levels of blood lactate in a primarily aerobic metabolism. It is assumed that this rest period would mainly affect the mechanisms of cardioventilatory recovery. However, our research group has observed in preliminary trials (unpublished data) that the combination of resistance exercises (in the form of circuit training), without rest between exercises, could keep blood lactate concentrations low and stable. The results stated in this study have important implications for our understanding of the load intensity and the recovery time that regulate ventilatory efficiency in a predominantly aerobic metabolism in HS exercise. Probably, a discontinuous constant-load HS test might induce a similar metabolic intensity and ventilatory efficiency as occurred during continuous constant-load cycle ergometer test. Further studies are needed to determine if the hypothetical increase in VO_2 and ventilation associated with a continuous protocol without recovery time between series would increase ventilatory efficiency in the resistance exercises to LT intensity.

CONCLUSIONS

Our findings showed that:

1) Cardioventilatory response was lower in HS exercise than in cycle ergometer during a constant-load test at LT intensity.

2) Ventilatory efficiency was equally efficient in the HS resistance exercise and in cycle ergometer exercise in a predominantly aerobic metabolism, which could have a significant impact in healthy people.

3) There was no correlation between the OUES and the slope of the VE/VCO_2 in the two exercise modalities analyzed. Those subjects who showed greater ventilatory efficiency in the HS did not achieve higher ventilatory efficiency in the cycle ergometer.

4) Performing a constant-load HS protocol at LT intensity does not generate significant cardiorespiratory stress, while ventilatory efficiency is maintained and muscle strength and local muscular endurance, as well as gross mechanical efficiency, may improve according to previous findings of our research group.

Further research is needed to analyze ventilatory efficiency for better understanding of ventilatory mechanisms that conditioning resistance exercises performance in a predominantly aerobic metabolism.

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10. DISCUSIÓN

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Esta tesis presenta tres estudios que profundizan principalmente en el conocimiento de la evaluación del VO_{2sc} de la eficiencia ventilatoria y mecánica en los ejercicios con resistencias en un protocolo de carga constante a intensidad de LT. Es por ello que se abordan los siguientes aspectos:

1. La evaluación del VO_{2sc}, la EE y la GME en el ejercicio de HS durante pruebas de carga constante a intensidad de LT para poder discutir los resultados con estudios similares en ejercicios de resistencia.

2. La comparación del VO_{2sc}, la eficiencia y/o economía, las respuestas metabólicas y la fatiga mecánica entre los ejercicios con resistencias y los ejercicios de resistencia, como son la HS y el CYC, en pruebas de carga constante a intensidad de LT.

3. Comparar las respuestas cardiorrespiratorias y la eficiencia ventilatoria entre los ejercicios con resistencias (HS) y los ejercicios de resistencia (CYC), mediante la pendiente del VE/VCO_2 y mediante el OUES en una prueba de carga constante a intensidad LT, y determinar la relación existente entre el OUES y la pendiente del VE/VCO_2 entre ellas y entre ambas modalidades de ejercicio.

1. Evaluación del VO_{2sc}, la EE y la GME

Respecto a la necesidad de evaluar el VO_{2sc}, la EE y la GME, se iniciaron los procesos experimentales utilizando el protocolo de Sousa et al. (57), pero no era útil ya que al implementarlo en los sujetos, en el ejercicio de HS, no era posible determinar el LT con los valores de lactato en sangre extraídos. No había ningún otro estudio que utilizara un protocolo para establecer el LT en el ejercicio de la HS, excepto el protocolo realizado por Simões et al. (92), que por los mismos motivos fue descartado por nuestro grupo de investigación. Como consecuencia, se tuvo que diseñar un test capaz de establecer el LT en una prueba incremental de HS.

Una vez determinado el LT se realizó la prueba de HS a carga constante a intensidad de LT, que al no disponer de referencias previas se volvió a diseñar un protocolo propio donde las concentraciones de lactato se mantuvieran estables en un metabolismo predominantemente aeróbico. Lograr que las concentraciones de lactato fueran inalterables a lo largo del protocolo a carga constante fue el primer paso para conseguir respuestas cardiorrespiratorias estables y, por tanto, poder analizar la cinética del VO_2 a lo largo de la prueba.

Aunque se han observado conclusiones comparables en varios estudios que analizan la relación entre el VO_2 y la GME en pruebas de ciclismo prolongados a carga constante (116), en la actualidad no hay estudios disponibles sobre el VO_{2sc}, EE, HSE o GME en sujetos que realicen ejercicios con resistencias en un test de carga constante a intensidad de LT con niveles relativamente bajos de lactato circulante en sangre (~3,3 $mmol/L^{-1}$). Esta carencia de conocimiento refuerza la necesidad de investigar en una modalidad de ejercicio tan utilizada tanto en el rendimiento como en el ámbito del fitness: los ejercicios con resistencias.

Curiosamente, aunque se pudo observar un comportamiento similar del VO_{2sc} en diferentes modalidades de ejercicio (es decir, HS de nuestro estudio frente a ciclismo), la etiología del ejercicio con resistencias a intensidad de LT es incierta porque la carga a intensidad de LT significa la carga más alta que no induce un aumento mayor del $VO_{2sc.}$ (61). En teoría, el VO_{2sc} en el protocolo constante de la HS a intensidad de LT debería ser inexistente o muy bajo. Sin embargo, se observó un incremento lento del VO_{2sc} similar al reportado por ciclistas profesionales a una intensidad superior al LT (80% VO_{2max}). Aunque en este primer estudio no se comparó el ejercicio de la HS con ningún ejercicio de resistencia, se sospechó que este incremento del VO_{2sc} a intensidad de LT, induciría una fatiga mecánica más acuciada que en el ejercicio del cicloergómetro a la misma intensidad LT. Esta idea fue respaldada por los hallazgos anteriores de nuestro grupo de investigación (8), donde se observaron pérdidas significativas en la altura y la producción de potencia solo en el ejercicio de HS y no en el ciclismo, después de aplicar un test de salto (CMJ) al final de la prueba de carga constante a intensidad de LT.

Probablemente, estos hechos sugieren una relación causal entre los mecanismos que inducen a la pérdida de fuerza de las extremidades inferiores y el aumento del VO_2 al final del ejercicio de carga constante a intensidad del LT (117). Se cree que la disminución en la eficiencia muscular dependiente de la intensidad está asociada con el desarrollo progresivo de la fatiga muscular (118). Encontramos que el VO_{2sc} podría determinarse por un aumento en la absorción de O_2 en las extremidades inferiores (64), lo que sugiere que el VO_{2sc} se activa principalmente en el músculo que se contrae y los factores centrales tienen una influencia menor de su amplitud (119).

A pesar de ello, los mecanismos exactos que causan el VO_{2sc} durante el ejercicio a intensidad submáxima aún no se conocen completamente. Se supone que el fenómeno del VO_{2sc} puede explicarse por el cambio en la GME, que estima los efectos de la alcalinización de la sangre sobre la pérdida gradual de la eficiencia muscular (59). Otros estudios han determinado que una disminución del GME coincide con el aumento significativo del VO_2 durante el ejercicio submáximo repetido (120).

Los resultados de GME reportados en nuestro primer estudio son más altos que los obtenidos en ciclistas profesionales a la intensidad de carga del LT y del punto de compensación respiratoria durante un test en rampa (74,75).

Los mecanismos fisiológicos de la disminución de la GME en los ejercicios con resistencias en una prueba de carga constante a intensidad de LT son totalmente desconocidos. Los valores altos encontrados en nuestro estudio (~44%), en comparación con otros, se atribuyen probablemente a las características del entrenamiento con resistencias. En el único estudio que encontramos donde se analizó la GME en los ejercicios con resistencias, Villagra et al. encontraron un VO_2 más alto y una GME más baja (aproximadamente 13-20%) a medida que la carga aumentaba (121). En su protocolo se realizaron 24 sentadillas por minuto y 96 sentadillas en 4 minutos con recuperación total entre series. En nuestro protocolo experimental, ejecutamos 15 repeticiones de HS en 30 segundos por serie, en el que los niveles de lactato en sangre y las respuestas del VO_2 se mantuvieron estables durante la prueba de carga constante a intensidad de LT (8,10). Las diferencias de GME observadas entre nuestros estudios y los de Villagra et al. podrían atribuirse a los diferentes protocolos experimentales aplicados en dichos estudios (121). En ambos estudios se utilizaron cargas ligeras, por lo que las diferencias podrían producirse por las repeticiones y por la duración establecidas en cada serie y en cada tipo de ejercicio: HS vs. sentadilla completa. Nuestros hallazgos dieron pie a interpretar que la forma de realizar el ejercicio (media sentadilla vs. sentadilla completa) también podría ser un componente diferenciador en la evaluación del VO_{2sc}, la GME y la EE.

2. La comparación del VO_{2sc}, la eficiencia y/o economía, las respuestas metabólicas y la fatiga mecánica entre los ejercicios con resistencias (HS) y los ejercicios de resistencia (CYC)

Los sorprendentes hallazgos del primer estudio en el comportamiento del VO_{2sc}, la GME y la EE en un protocolo constante a intensidad LT, condujeron a la necesidad de buscar más evidencias comparando el ejercicio de la HS con el más usual de los ejercicios de resistencia en este tipo de evaluaciones, el cicloergómetro.

El principal descubrimiento de este estudio fue que el VO_{2sc} y la EE aumentaron lentamente sólo en la prueba de HS de carga constante a una intensidad LT. Estos resultados podrían justificar, en parte, una disminución del rendimiento en el salto (fatiga) solo después de la prueba de HS. Los valores absolutos del VO_{2sc} en la prueba de la HS de nuestro estudio fueron ligeramente superiores (141,4 $mL.min^{-1}$) a los observados en cicloergómetro (131,8 $mL.min^{-1}$) en sujetos jóvenes sanos, y a los reportados en otro estudio con ciclistas profesionales (130 $mL.min^{-1}$) a carga constante a una intensidad por encima del LT (80% VO_{2max}) (122). Estos resultados difieren en demasía de los obtenidos por triatletas bien entrenados durante una prueba a carga constante al 90% del VO_{2max} (269 $mL.min^{-1}$) en ciclismo y corriendo (21 $mL.min^{-1}$).

En la actualidad, estas variaciones del VO_{2sc} no se comprenden completamente, aunque podrían estar relacionadas con la diferencia en la magnitud de VO_{2sc} entre los modos de ejercicio y la intensidad de carga (112,114), el estado de entrenamiento de los sujetos (61) y el tipo de pruebas de carga constante prolongadas (116).

Los mecanismos fisiológicos que provocan el aumento del VO_{2sc} durante la prueba de HS son inciertos, porque el ejercicio de carga constante a la intensidad $LT_{1,}$ no provocaría en teoría un aumento del VO_{2sc} (61). La cinética del VO_2 observada durante la prueba de cicloergómetro de carga constante justificó un estado estable en el VO_2 y EE a la intensidad del LT_1, sin producirse un incremento significativo a lo largo de la prueba como aconteció en el ejercicio de la HS. En consecuencia, el lactato sanguíneo aumentó por encima de los valores de reposo y se mantuvo estable durante ambas pruebas a carga constante (8).

Si el VO_2 continuó aumentando significativamente, especialmente al final de la prueba de carga constante de HS, podría suponerse que el incremento del VO_{2sc} se asociaría con la aparición de la fatiga y una probable disminución en la eficiencia muscular, por lo que el lactato en sangre debería acumularse a una velocidad constante o creciente en respuesta a la transición hacia un metabolismo predominantemente anaeróbico (123).

Realmente, la única hipótesis que se confirmó fue un aumento en el VO_{2sc} y EE vinculados a la fatiga de las extremidades inferiores solo al final de la prueba de HS. Quizás, el tiempo de recuperación acumulado entre series en la prueba de HS fue un factor clave para el mantenimiento de los niveles de lactato en sangre estables en un metabolismo aeróbico. Aunque el tiempo de descanso de 30 segundos han indicado efectos insignificantes sobre la cinética del lactato durante protocolos discontinuos (124), el protocolo de HS causó una falta relativa de suministro de O_2 en el músculo, sugiriendo además que un porcentaje importante de la energía derivada del metabolismo anaeróbico podría no ser cuantificada por medición del intercambio metabólico de gases (125).

Otro mecanismo factible, que ayudaría a comprender mejor la etiología del VO_{2sc} en los ejercicios de resistencia, es la relación entre el ligero aumento del VO_2 pulmonar con el incremento del VO_2 en el músculo. Se ha sugerido que el aumento del VO_2 de las piernas podría explicar el 85% del aumento del VO_2 pulmonar (64). Probablemente, el VO_{2sc} descubierto en el ejercicio HS incrementó el VO_2 en las piernas dentro del músculo activo a una magnitud mayor que en el ejercicio de CYC y, en consecuencia, la EE aumentó sólo durante la prueba de la HS.

El aumento del VO_{2sc} y EE probablemente estaría asociado con un aumento en el costo de la producción de fuerza ATP y/o un aumento del costo de O_2 de la resíntesis de ATP (126,127). Este mecanismo energético provocaría un reclutamiento forzado de unidades motoras más grandes y menos eficientes desde el punto de vista oxidativo, para compensar la producción de fuerza atenuada en aquellas unidades motoras ya activas. Una reducción preferencial del glucógeno de las fibras de tipo I (128) y el reclutamiento de fibras tipo II (60,62) ha sido postulado como la más aceptable explicación para el VO_{2sc} (59).

Al respecto, han sido detectados patrones de agotamiento de glucógeno en fibras de tipo I/II, confirmando que se activaron tanto fibras musculares glucolíticas de contracción rápida como fibras musculares oxidativas de contracción lenta durante el ejercicio de ciclismo de alta intensidad al 80% de VO_{2max}. Sin embargo, cuando el ejercicio de ciclismo se realizó a intensidad moderada (50% de VO_{2max}), solo se reclutaron fibras de tipo I y no se observó un VO_{2sc} (129). Estos hallazgos sugieren que el reclutamiento de fibras tipo I por este mecanismo probablemente ocurrió durante la prueba de CYC de carga constante, razón por la cual no se produjo un incremento significativo del VO_2 y no se indujo una fatiga en las extremidades inferiores. El objetivo de este estudio no fue evaluar el reclutamiento gradual de fibras asociado con el coste energético, por lo que nuestros argumentos se basan en los resultados de estos estudios. Sin embargo, es plausible proponer que el VO_{2sc} y el correspondiente aumento en la EE podría estar relacionado con la fatiga observada en el ejercicio de la HS (125).

En relación a la GME, al no existir estudios previos de ejercicios con resistencia, se comparó la prueba de HS con el ejercicio del CYC encontrando valores similares a los obtenidos por ciclistas bien entrenados (~18%) durante pruebas de larga duración a carga constante e intensidad moderada. En el ejercicio de la HS, verificamos nuestros hallazgos previos con valores de GME de ~44% respecto a valores de ~24-26% en ciclistas profesionales a intensidad de LT y el punto de compensación respiratoria durante una prueba de rampa (74). Asimismo, en otros estudios con esquiadores de fondo de clase mundial se han encontrado valores de GME más bajos de 14–16%

(130). Estos valores refuerzan la idea de que la GME está condicionada por la modalidad del ejercicio.

Además, sospechamos que valores más altos de VO_{2sc}, de EE y la no pérdida de GME a lo largo de la prueba de HS de carga constante en comparación con la prueba de CYC, fueron principalmente debido al tipo de acción muscular involucrada en ambas modalidades de ejercicio. La ejecución de la prueba de HS se caracteriza por tener acciones musculares excéntricas y concéntricas; por el contrario el ciclismo prioriza las acciones musculares concéntricas (131). Se ha demostrado que hay un mayor incremento en el costo de O_2 en el ejercicio de la sentadilla sin rebote (solo concéntricas) en comparación con la sentadilla que implica acciones musculares combinadas excéntricas y concéntricas. En este mismo estudio se observó que la realización de acciones musculares combinadas, excéntricas y concéntricas, estimulan una mayor eficiencia mecánica que el ejercicio de la HS puramente concéntrico (121). El estiramiento previo permite el almacenamiento de energía elástica en los componentes elásticos (músculos y tendones), produciendo una energía extra que se libera durante el ciclo de acortamiento, probablemente disminuyendo el costo de O_2.

De hecho, se ha demostrado que varios factores afectan a la eficiencia mecánica y la fatiga durante el ejercicio, incluidas las propiedades musculares (122)as assessed by surface electromyography (EMG, el tipo de contracción muscular, el tipo de acción muscular y la metodología del ejercicio (producción y duración de fuerza máxima frente a la submáxima) (132). Estos hechos invitan a pensar que el pre-estiramiento podría ayudar a prevenir un incremento del VO_{2sc}, reduciendo el VO_2 y aumentando la eficiencia en el ejercicio de la HS en mayor medida que el observado en el CYC, evitando un mayor reclutamiento de fibras tipo II.

Otro factor a tener en cuenta es la masa muscular involucrada durante el ejercicio ya que varios estudios han demostrado una disminución del VO_{2sc} en carrera con respecto al ciclismo (112,113) o un aumento relativo más alto en el VO_2 por unidad de tiempo durante una ergometría de brazos que en una prueba de ciclismo cuando se trataba de una masa muscular más baja o cuando el ejercicio se centró en un grupo muscular específico (114). Aunque los principales músculos implicados en la HS y en los ejercicios de ciclismo son los extensores de la rodilla, durante la posición vertical y de pie en la HS se produce una mayor activación de otros grupos musculares que son mínimamente activados en la posición sentada y sin carga añadida en el cicloergómetro (CORE, trapecio, dorsal, deltoides, etc.). Probablemente, la mayor masa muscular involucrada en el ejercicio de HS podría ayudar a aumentar la eficiencia de todo el cuerpo disminuyendo el costo de O_2. Estas conjeturas incitan a la realización de más estudios que evalúen la incidencia de una implicación de más grupos musculares durante las pruebas en las que se analice la GME.

Finalmente, varios estudios han comparado las respuestas ventilatorias y el VO_{2sc} entre varios ejercicios a la misma intensidad relativa (112,114). El comportamiento de VO_2 y VO_{2sc} dependen del ejercicio y la intensidad, aunque se evalúen a la misma intensidad relativa o metabólica. El entrenamiento con resistencias es típicamente anaeróbico en su naturaleza. Pensamos que la aportación más importante de este estudio es que los ejercicios con resistencias podrían adquirir propiedades metabólicas aeróbicas seleccionando una carga adecuada y controlando la recuperación y el tiempo de ejecución durante las series.

3. Comparar las respuestas cardiorrespiratorias y la eficiencia ventilatoria entre los ejercicios con resistencias (HS) y los ejercicios de resistencia (CYC), mediante la pendiente del VE/VCO2 y mediante el OUES en una prueba de carga constante a intensidad LT. Determinar la relación existente entre el OUES y la pendiente del VE/VCO2 en ambas modalidades de ejercicio

Una vez comparada la cinética del VO_2, la EE y la eficiencia mecánica entre ambas modalidades de ejercicio, nos resultaba inquietante realizar una comparativa en la eficiencia ventilatoria entre ambas modalidades de ejercicio. Los ejercicios de resistencia como el correr, ciclismo, etc., son usualmente empleados para el desarrollo del fitness cardiorrespiratorio y los ejercicios con resistencias para el muscular.

A pesar de que la respuesta cardiorrespiratoria fue mayor en el ejercicio del cicloergómetro que en la prueba de HS, la eficiencia ventilatoria, calculada mediante la pendiente del VE/VCO_2 y el OUES, fue muy similar en ambas modalidades de ejercicio. Además, los valores detectados especialmente en el lactato y en el RER, y el comportamiento estable observado en las variables cardiorrespiratorias justifican un metabolismo principalmente aeróbico en ambos ejercicios.

Probablemente, durante una prueba de carga constante a una intensidad moderada (LT) la relación entre la VE y el VCO_2 y el VO_2 es normalmente estable y uniforme antes de la aparición de la compensación ventilatoria para la acidosis láctica inducida por el ejercicio (79), lo que justificaría, al menos en parte, las similitudes detectadas en el VE/VCO_2 y OUES entre ambas modalidades de ejercicio en el mismo estado metabólico.

Los resultados de las pendientes del VE/VCO_2 y OUES obtenidos en ambos ejercicios se consideraron normales y comparables a otros estudios con adultos sanos (83,87,133). En ciclistas de élite jóvenes la pendiente de VE/VCO_2 fue similar (alrededor de 28) a nuestro estudio, pero el OUES fue mayor: 3.8 frente a 2.5 en nuestro estudio (82). La diferencia podría deberse a la novedosa metodología utilizada en nuestro estudio y la mayor capacidad cardiorrespiratoria de los ciclistas jóvenes de élite. Además, no se detectaron estudios disponibles para la comparación de la pendiente VE/VCO_2, en el cicloergómetro o en la HS en una prueba de carga constante a intensidad del LT. Sin embargo, nuestros resultados sobre la eficiencia ventilatoria fueron muy similares a los obtenidos en otros estudios en ejercicios de resistencia (ciclismo) a la intensidad del umbral anaeróbico (82), tal vez porque ambas intensidades (umbral anaeróbico y LT) reflejan un momento metabólico similar, a partir del cual las concentraciones de lactato comienzan a aumentar.

Un aspecto sorprendente de este estudio fueron los valores casi idénticos en la eficiencia ventilatoria observada en las pruebas de HS y CYC. Los estudios que comparan la pendiente VE/VCO_2 y los OUES en diferentes tipos de ejercicios no son habituales. Por lo tanto, existe una falta significativa de información sobre qué modalidad de ejercicio podría inducir una mayor eficiencia ventilatoria. Nuestros hallazgos muestran que dos tipos de ejercicio con diferentes respuestas cardiorrespiratorias inducen la misma eficiencia ventilatoria a la misma intensidad metabólica. Durante las pruebas de ejercicio incremental (134), no se encontraron cambios significativos entre las pruebas con tapiz rodante y con cicloergómetro. Un estudio comparó el OUES en 17 sujetos sanos en dos modalidades de ejercicio, observando valores más altos en la prueba de esfuerzo en tapiz rodante en comparación con el cicloergómetro (133). Aunque se necesita evidencia adicional, la eficiencia ventilatoria podría depender del tipo de ejercicio, el protocolo de prueba y el modo de evaluar la eficiencia ventilatoria (pendiente de OUES frente a VE/VCO_2).

No queda claro qué factores contribuyen a modificar la eficacia de la ventilación durante el ejercicio, pero los postulados establecidos a través de esta discusión pueden ser más relevantes en la evaluación en el campo clínico que en la valoración de la aptitud física y el rendimiento deportivo. Este pensamiento se fundamenta en que la pendiente del VE/VCO_2 no se modificó en ciclistas de élite después de 16 semanas de entrenamiento (82) y tampoco, independientemente del sexo, en niños (135) y adultos sanos (79) que realizaban ejercicio. El entrenamiento no mejoró el OUES en sujetos sanos (136) y podría tener un efecto limitado en los atletas (82). Sin embargo, en presencia de algún tipo de patología asociada con una reducción en la masa muscular, como sarcopenia o insuficiencia cardíaca, los ejercicios con resistencias a la intensidad LT podrían ser una excelente alternativa para mejorar la eficiencia de la ventilación.

Finalmente, esperábamos que los sujetos con una menor pendiente de VE/VCO_2 (mayor eficiencia) incrementaran su OUES en cada una de las pruebas. La falta de correlación significativa entre los OUES y la pendiente del VE/VCO_2 en las dos modalidades de ejercicio analizadas indica que los sujetos que mostraron una mayor eficiencia ventilatoria en la HS no lograron una mayor eficiencia ventilatoria en el cicloergómetro.

11. LIMITACIONES DEL ESTUDIO

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Hay algunas limitaciones en este estudio con respecto al protocolo de ejercicios de la HS, que deben considerarse.

- La 1RM de los sujetos puede variar de la sesión de la prueba inicial a la siguiente; por lo tanto una prueba de reevaluación hubiera sido conveniente para mejorar los resultados confiables de la prueba al reducir los efectos del sesgo sistemático.

- La carga utilizada (% 1RM) durante la sesión de la prueba incremental y potencia de salida desarrollada en cada repetición del ejercicio de la HS también podría modificarse ligeramente durante la prueba de carga constante a intensidad de LT.

- Hubiera sido interesante analizar la relación existente entre la eficiencia ventilatoria y parámetros máximos como el VO_2 pico. Sin embargo, en nuestro ánimo estaba el generar un protocolo de moderada intensidad, prolongado en el tiempo que no produjera un estrés cardiorrespiratorio importante, ciñéndonos a los pocos estudios que efectuaron protocolos constantes en el umbral aeróbico.

- Los procedimientos experimentales establecidos en ambas pruebas incrementales abren un debate controvertido con respecto a la ubicación del LT_1. En consecuencia, la intensidad relativa o la carga externa prescrita en cada ejercicio podría haber sido diferente durante ambas pruebas de carga constante. En este caso, se produciría un sesgo importante al comparar la eficacia ventilatoria, las respuestas cardiorrespiratorias y metabólicas entre ambos ejercicios. Sin embargo, los resultados obtenidos durante la prueba incremental revelaron que la detección de LT_1 en ambos ejercicios, podría ocurrir en un tiempo metabólico equivalente y una intensidad de ejercicio similar. Esta idea se basa en el hecho de que no se encontraron diferencias significativas en el VO_2, la frecuencia cardíaca, las concentraciones de lactato en sangre y el RPE entre el HS y el CYC en el LT_1.

12. CONCLUSIONES

12. CONCLUSIONES

Tras los estudios de la presente tesis podemos concluir:

1. El ejercicio de la HS a carga constante a intensidad de LT induce un mayor EE y un incremento del VO_{2sc} que el ejercicio del CYC.

a. Quizás, este sea el factor condicionante para detectar una mayor fatiga mecánica en el ejercicio de la HS.

b. La mayor masa muscular implicada en el ejercicio de la HS podría condicionar un mayor incremento del VO_{2sc} y de la EE.

2. La eficiencia/economía es mayor en el ejercicio de la HS que en CYC.

a. Probablemente, sea debido a la mayor implicación de las acciones musculares excéntricas en el ejercicio de la HS.

b. Sin embargo, la reducción de la GME/HSE observada a lo largo de la prueba fue la misma en ambas modalidades de ejercicio.

3. Un mejor conocimiento del comportamiento de VO_{2sc}, EE, HSE y GME (generalmente utilizado en ejercicios de resistencia) nos permitiría aumentar el rendimiento y descubrir el potencial de los ejercicios con resistencias en un metabolismo predominantemente aeróbico.

a. El entrenamiento con resistencias a una intensidad de carga equivalente al LT podría mejorar la resistencia muscular localizada y la eficiencia muscular de todo el cuerpo.

b. Esto permitiría una recuperación más rápida de los grupos musculares de una sesión a otra en los programas de acondicionamiento físico.

4. A pesar de que las respuestas cardiorrespiratorias fueron aumentadas en el ejercicio del cicloergómetro, la eficiencia ventilatoria fue igualmente eficaz en el ejercicio de HS que en el ejercicio en CYC en un metabolismo predominantemente aeróbico, lo que podría tener un impacto significativo en el ámbito clínico.

a. La realización de un protocolo de HS de carga constante a intensidad LT no genera tanto estrés cardiorrespiratorio como el cicloergómetro, mientras que la eficiencia ventilatoria se mantiene y la fuerza y la resistencia muscular local, así como la eficiencia mecánica bruta, se podrían incrementar.

b. En enfermedades o patologías en las que el acondicionamiento de la masa muscular y/o la eficiencia ventilatoria juega un papel importante en el proceso de rehabilitación. La prescripción de ejercicios con resistencias en un metabolismo aeróbico podría ser una alternativa adecuada.

c. No existe ningún tipo de relación entre la pendiente del VE/VCO2 y el OUES en ambas modalidades de ejercicio.

13. LÍNEAS DE INVESTIGACIÓN

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1. Estos hallazgos podrían ser una alternativa interesante para los procesos de rehabilitación física y recuperación de enfermedades asociadas con una pérdida de fuerza y masa muscular, donde la eficiencia ventilatoria juegue un papel determinante. Por ejemplo, los pacientes con insuficiencia cardíaca se caracterizan por una pérdida significativa de masa muscular, y estos mismos mecanismos fisiológicos están estrechamente relacionados con la disnea y la fatiga ventilatoria (137). En este caso, la eficiencia ventilatoria está relacionada con la gravedad de la insuficiencia cardíaca con una fracción de eyección reducida (47,138) y, como consecuencia, la eficiencia ventilatoria deficiente está relacionada con una mayor morbilidad y mortalidad. Además, es común diagnosticar la fuerza y la pérdida muscular (sarcopenia) en adultos mayores. La sarcopenia es un síndrome prevalente asociado con la mortalidad prematura en ancianos (139).

2. Realizar un programa de ejercicios con resistencias a intensidad de LT, podría inducir un menor estrés cardiorrespiratorio (8), controlando los niveles de lactato en sangre (acidosis) en un metabolismo predominantemente aeróbico, aumentando la eficiencia mecánica bruta (125) y, como lo muestra nuestro estudio, produciendo la misma eficiencia ventilatoria que el ejercicio de cicloergómetro a la misma intensidad metabólica. Está claro que la combinación de entrenamientos con resistencias y de resistencia han mejorado la capacidad de ejercicio y la función diastólica en pacientes con insuficiencia cardíaca con fracción de eyección reducida (140). En consecuencia, la combinación de ejercicios con resistencias y de resistencia podría ser una metodología adecuada para aumentar la respuesta cardiorrespiratoria (ejercicios de resistencia) por un lado y la fuerza y la resistencia muscular (ejercicios con resistencias) por otro lado.

3. No podemos dejar de mencionar que el tiempo de recuperación establecido entre cada serie es un factor clave para mantener niveles bajos y estables de lactato sanguíneo en un metabolismo principalmente aeróbico. Se supone que este período de descanso afectaría principalmente los mecanismos de recuperación cardiorrespiratoria. Sin embargo, nuestro grupo de investigación ha observado en ensayos preliminares (datos no publicados) que la combinación de ejercicios con resistencias (en forma de entrenamiento en circuito), sin descanso entre los ejercicios, podría mantener bajas y estables las concentraciones de lactato en la sangre. Se necesitan más estudios para determinar si el aumento hipotético en el VO_2 y la ventilación asociados con un protocolo continuo sin tiempo de recuperación entre series aumentaría la eficiencia ventilatoria en los ejercicios con resistencias a la intensidad de la LT. Este conocimiento científico podría ser un avance importante en la evaluación de ejercicios con resistencias para la promoción deportiva del rendimiento y la salud.

4. Sería esencial analizar otros ejercicios con resistencias (por ejemplo, press de banca, press de piernas, etc.) y compararlos o combinarlos con ejercicios de resistencia (por ejemplo, ciclismo, caminar, correr, etc.) para determinar qué tipo de ejercicios son más adecuados para cada segmento de población según el objetivo del programa de ejercicios.

5. Sería interesante también, desde perspectiva de género, realizar estudios en mujeres para ver si se pueden utilizar los mismos protocolos y ver si se obtienen resultados similares a los reportados en este estudio por nuestro grupo de investigación.

14. REFERENCIAS

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15. ANEXOS

Oxygen Uptake Slow Component and the Efficiency of Resistance Exercises

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Abstract

Garnacho-Castaño, MV, Albesa-Albiol, L, Serra-Payá, N, Gomis Bataller, M, Pleguezuelos Cobo, E, Guirao Cano, L, Guodemar-Pérez, J, Carbonell, T, Domínguez, R, and Maté-Muñoz, JL. Oxygen uptake slow component and the efficiency of resistance exercises. *J Strength Cond Res* XX(X): 000–000, 2018—This study aimed to evaluate oxygen uptake slow component ($\dot{V}O_2sc$) and mechanical economy/efficiency in half squat (HS) exercise during constant-load tests conducted at lactate threshold (LT) intensity. Nineteen healthy young men completed 3 HS exercise tests separated by 48-hour rest periods: 1 repetition maximum (1RM), incremental-load HS test to establish the %1RM corresponding to the LT, and constant-load HS test at the LT. During the last test, cardiorespiratory, lactate, and mechanical responses were monitored. Fatigue in the lower limbs was assessed before and after the constant-load test using a countermovement jump test. A slight and sustained increase of the $\dot{V}O_2sc$ and energy expended (EE) was observed ($p < 0.001$). In blood lactate, no differences were observed between set 3 to set 21 ($p > 0.05$). A slight and sustained decrease of half squat efficiency and gross mechanical efficiency (GME) was detected ($p < 0.001$). Significant inverse correlations were observed between $\dot{V}O_2$ and GME ($r = -0.93$, $p < 0.001$). Inverse correlations were detected between EE and GME ($r = -0.94$, $p < 0.001$). Significant losses were observed in jump height ability and in mean power output ($p < 0.001$) in response to the constant-load HS test. In conclusion, $\dot{V}O_2sc$ and EE tended to rise slowly during constant-load HS exercise testing. This slight increase was associated with lowered efficiency throughout constant-load test and a decrease in jump capacity after testing. These findings would allow to elucidate the underlying fatigue mechanisms produced by resistance exercises in a constant-load test at LT intensity.

Key Words gross mechanical efficiency, lactate threshold, mechanical fatigue, energy expended, half squat

Introduction

Recently, several studies have focused on incremental resistance exercise tests (10,13) designed to identify the point of transition between aerobic and anaerobic metabolism, recognized as the lactate threshold (LT) (3). The LT is defined as the load intensity during incremental exercise at which blood lactate concentrations increase exponentially (39). This is considered the load intensity that supports the prescription of resistance training and monitoring of training progress for the healthy population, athletes, and those undergoing rehabilitation (39).

During prolonged constant-load resistance exercises tests conducted at a load intensity equivalent to the LT, a stabilization is observed in blood lactate levels and in cardiorespiratory response in leg press (10) and half squat (HS) exercise (14), as also occurs in endurance exercises (13). It is known that oxygen uptake ($\dot{V}O_2$) tends to slowly rise during any constant work rate exercise test involving sustained lactic acidosis, surpassing the primary component initiated at exercise onset. This $\dot{V}O_2$ response, known as the "$\dot{V}O_2$ slow component" ($\dot{V}O_2sc$), is defined as the continued increase in $\dot{V}O_2$ beyond the third minute of exercise (12) until a delayed steady state is attained or maximal $\dot{V}O_2$ is reached (43). During long-term constant-load exercise, the $\dot{V}O_2sc$ kinetics increases the energy expenditure above that predicted from the submaximal $\dot{V}O_2$ work-rate relationship, leading to a reduced work efficiency and premature fatigue.

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Thus, a limited $\dot{V}O_2$sc might be an important parameter to determine endurance performance (12).

The scientific literature indicates several physiological factors that individually or jointly could influence on the $\dot{V}O_2$sc behavior, including muscle fiber type (34), type of muscle action and contraction (35), pattern of motor unit recruitment, and type of exercise (6). It has been reported that the $\dot{V}O_2$sc is lower in running compared with cycling exercise (6) and higher in arm-crank than leg-cycle exercises (19), indicating that the $\dot{V}O_2$sc is exercise-dependent.

Although these studies have focused on evaluating the $\dot{V}O_2$sc in endurance exercises, the $\dot{V}O_2$sc phenomenon in resistance exercises during a long-term constant-load exercise test has not been explored. It is tempting to suggest that knowledge of $\dot{V}O_2$sc behavior in resistance exercises might help to elucidate the underlying fatigue mechanisms produced during prolonged constant-load testing. Garnacho-Castaño et al. (14) observed significant losses in height and mean power during the countermovement jump (CMJ) test only in HS exercise (not in cycling) measured at the end of a constant-load exercise test at LT intensity. This decrease in jumping ability after the constant-load HS test could be related to a slow rise in $\dot{V}O_2$, and the corresponding increase in energy cost would be associated with progressive fatigue (16). This mechanical fatigue, presumably prompted during a constant-load HS test, would stimulate a preferential glycogen depletion of type I fibers and induce a forced recruitment of type II fibers (21). In addition, a key determinant of the $\dot{V}O_2$sc is the change in gross mechanical efficiency (GME), which estimates the effects of blood alkalinization on the gradual loss of muscle efficiency (12).

Table 1. Descriptive data related to 1RM incremental- and constant-load tests.*

Variables	Mean	*SD*
1RM in HS (kg)	204.9	45.9
Load at LT intensity (kg)	51.0	17.2
LT intensity (%1RM)	25.3	5.0
Lactate in constant test (mmol·L^{-1})	3.3	0.9
$\dot{V}O_2$ at LT intensity (L·min^{-1})	1.6	0.2
$\dot{V}O_2$ at LT intensity (ml·Kg^{-1}·min^{-1})	20.0	2.3
HR at LT intensity (b·min^{-1})	128.6	12.0
RER at LT intensity	0.93	0.0
HSE at LT (W·L^{-1}·min^{-1})	155.7	6.6
GME at LT (%)	44.9	2.0
EE at LT intensity (Kcal·min^{-1})	8.0	0.4

*1RM = 1 repetition maximum; HS = half squat; LT = lactate threshold; $\dot{V}O_2$ = oxygen uptake; HR = heart rate; RER = respiratory exchange ratio; HSE = half squat efficiency; GME = gross mechanical efficiency; EE = energy expended.

Half squat is one of the most popular exercises in resistance training programs. In scientific literature, the $\dot{V}O_2$sc and economy/efficiency responses to constant-load HS exercise performed at LT intensity are still unknown.

We hypothesized that, as $\dot{V}O_2$sc increases in a prolonged constant-load test at LT intensity, work efficiency in resistance exercises such as HS should be reduced, and therefore, it would be plausible to propose a causal inverse relationship between the $\dot{V}O_2$sc, energy expended (EE), and mechanical efficiency. This study aimed to evaluate the $\dot{V}O_2$sc kinetic, EE, and mechanical efficiency in HS exercise during prolonged constant-load tests conducted at an intensity equivalent to the LT.

Methods

Experimental Approach to the Problem

Participants performed 3 different tests between 9:00 AM and 15:00 PM (±3 hours) each day under the same environmental conditions (temperature: 21–25° C, atmospheric pressure: 715–730 mm Hg, and relative humidity: 40–50%), with a rest period between each test of 48 hours. The test protocols followed the guidelines established by our research group in previous studies (14): (a) 1 repetition maximum (1RM) HS test to determine the % loads to be used in the incremental test, (b) incremental-load HS test to establish the %1RM corresponding to the LT, and (c) constant-load HS test at the LT. In the HS constant-load test, acute cardiorespiratory and metabolic responses were recorded. A Smith machine (Matrix G1-FW161; Madrid, Spain) was used to ensure controlled movements. Mechanical fatigue in the lower limbs was assessed before and after the constant-load tests.

Subjects

The study participants were 19 young, healthy men, all students of the Physical Activity and Sport Sciences (age 21.7 ± 1.7 years; height, 180.5 ± 5.1 cm; body mass, 81.9 ± 9.5 kg; body mass index, 25.1 ± 2.2). Participants had at least 6 months of experience in strength training and all were accustomed to HS exercise. Four exclusion criteria were applied: (a) the use of any medication or performance-enhancing drugs, (b) any cardiovascular, metabolic, neurological, pulmonary, or orthopedic disorders that could limit exercise performance, (c) being an elite athlete, and (d) a 1RM of less than or equal to 150 kg in HS exercise.

Before the study outset, participants were informed of the tests, and written consent was obtained from each subject. The study protocol was approved by the Ethics Committee of the Alfonso X el Sabio University (Madrid, Spain) and adhered to the tenets of the Declaration of Helsinki.

One Repetition Maximum Half Squat Test. The HS test protocol included a standard warm-up for all subjects, involving 5 minutes of low-intensity running and 5 minutes of joint mobility and dynamic stretching exercises. This was

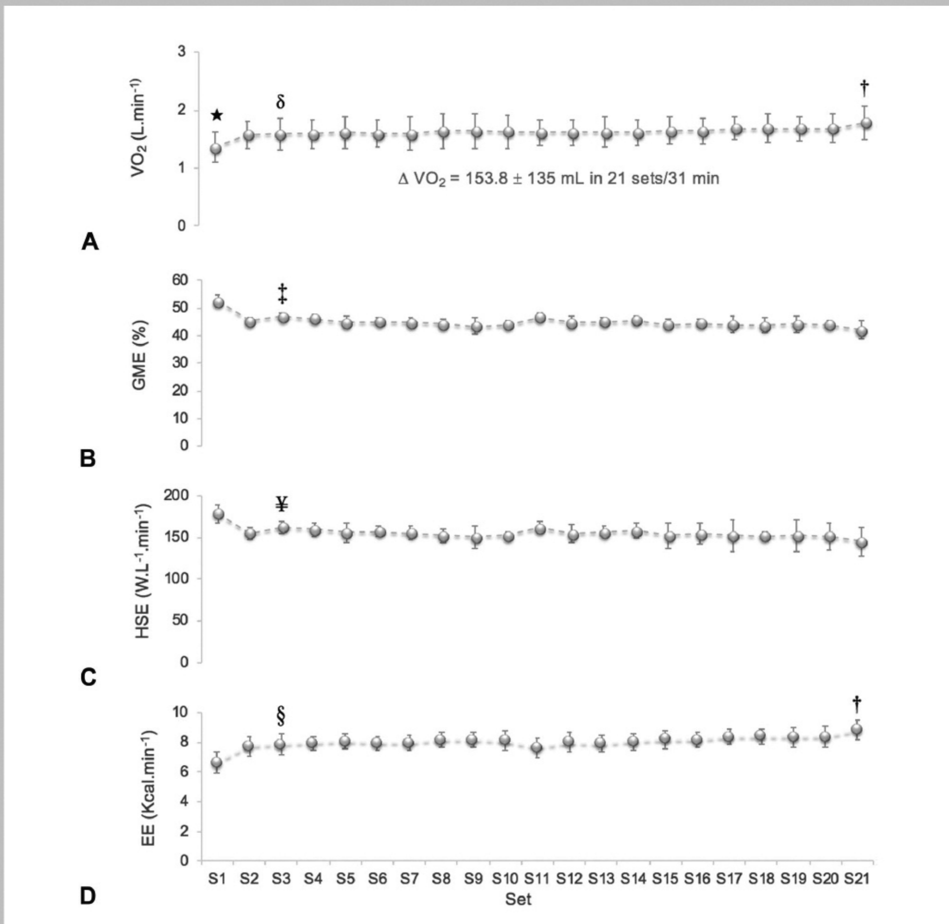

Figure 1. Slow component kinetics (A); gross mechanical efficiency (GME) (B); half squat efficiency (HSE) (C); and energy expended (EE) (D) during constant-load half squat (HS) test at lactate threshold intensity. ★Significant differences vs. checkpoints S3, S6, S9, S12, S15, S18, S21 ($p < 0.001$). δSignificant differences vs. checkpoints S6, S12, S15, S18, S21 ($p < 0.05$). ‡Significant differences vs. checkpoints S6, S9, S12, S15, S18, S21 ($p < 0.05$). ¥Significance differences vs. checkpoints S9, S12, S15, S18, S21 ($p < 0.05$). §Significant differences vs. checkpoints S6, S18, S21 ($p \leq 0.004$). † Significant differences vs. checkpoints S6, S12, S15 ($p < 0.05$).

followed by a specific warm-up consisting of 1 set of 3–5 HS repetitions at a relative intensity of 40–60% of the maximum perceived effort. Subjects commenced the 1RM test after a 2-minute rest. This involved 3–5 lifting attempts using increasing weights. The 1RM was defined as the last load lifted by the subject while completing a knee extension to the required position. The rest period between each attempt was 4 minutes.

The HS technique was specified in the protocol. The participants positioned themselves under the barbell in a standing position with the knees and hips fully extended, and legs spread at shoulder width. The barbell was placed on the upper back (trapezius muscle), approximately at the level of the acromion. The subject flexed the knees and hips (eccentric action) to lower the barbell in a controlled manner, until 90° flexion of the knees. From this position,

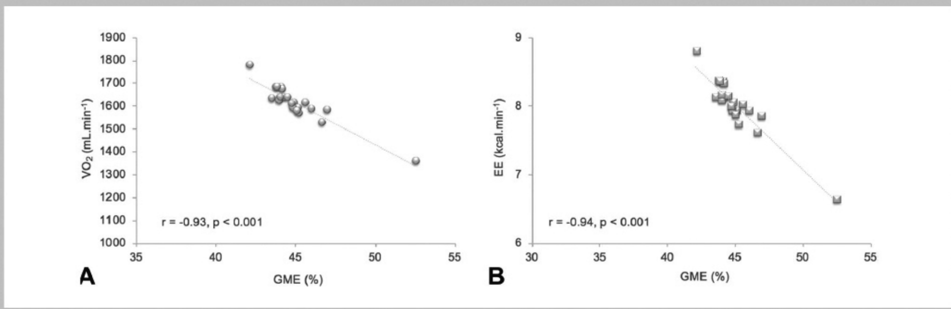

Figure 2. Relationship between (A) $\dot{V}O_2$ and gross mechanical efficiency (GME); (B) energy expended (EE) and GME.

the propulsive (concentric) muscle action was initiated until the knees and hips were fully extended.

Incremental Half Squat Test. Participants performed the same warm-up as in 1RM HS test. After a 2-minute rest, the incremental HS test was performed in sets at relative intensities of 10, 20, 25, 30, 35, and 40% 1RM as in previous studies (14,27). Each set lasted 1 minute and involved 30 repetitions of 2 seconds each (1 second for the eccentric phase and 1 second for the concentric phase). This rhythm was monitored with a metronome while an observer provided visual and verbal cues. A passive rest of 2 minutes was established between sets while the relative load (%1RM) was increased and blood samples were collected for lactate determination. The test was completed when the subject did not correctly perform repetitions or was unable to continue executing repetitions at the rhythm set for each set at the corresponding relative intensity (%1RM).

Blood samples (5 μL) were obtained by finger pricking 30 seconds after the end of each set/relative intensity (10, 20, 25, 30, 35, and 40% of 1RM), and lactate levels determined using a portable lactate analyzer (Lactate Pro LT-1710; Arkray Factory Inc., KDKCorporation, Shiga, Japan). The reliability of this device has been previously evaluated (28). All measurements were rigorously performed by the same expert evaluator.

The LT was established using the algorithm adjustment method based on the procedure described by Orr et al. (31), as the work intensity at which lactate concentrations start to increase in an exponential manner (42). The LT was located through computerized 2-segment linear regression by fixing both linear regression equations emerging for each segment at the point of intersection between a plot of blood lactate concentration and relative intensity. Data treatment was performed using the software package Matlab version 7.4 (MathWorks, Natick, MA, USA).

Constant-Load Half Squat Test at Lactate Threshold Intensity. Participants performed the same warm-up as in 1RM HS test. After 2 minutes, the constant-load HS test was conducted as 21 sets of 15 repetitions of 2 seconds (1 second of concentric exercise and 1 second of eccentric) guided by metronome, visual, and verbal cues. The duration of each set was 30 seconds, with a 1-minute rest period between sets; the complete constant-load test took 31 minutes.

Respiratory exchange data were recorded using a breath-by-breath open-circuit gas analyzer (Vmax spectra 29; Sensormedics, Corp., Yorba Linda, CA, USA), which had been previously calibrated. The following variables were monitored: minute ventilation (VE), volume oxygen consumed ($\dot{V}O_2$), volume carbon dioxide expired ($\dot{V}CO_2$), and respiratory exchange ratio (RER). Heart rate was monitored every 5 seconds by telemetry (RS-800CX; Polar Electro OY, Kempele, Finland).

Blood samples were obtained at rest and 30 seconds after the end of the HS sets (S) S3, S6, S9, S12, S15, S18, and S21, when lactate concentrations were determined as described above for the incremental test. The checkpoints of the lactate samples coincided with the following minutes of testing (M): S3/M4, S6/M8.5, S9/M13, S12/M17.5, S15/M22, S18/M26.5, and S21/M31 (test end).

The $\dot{V}O_2$sc was identified as the difference between $\dot{V}O_2$ at the end of exercise and at the end of the third minute of constant-load exercise ($\Delta\dot{V}O_2$, in $mL \cdot min^{-1}$). The latter was taken as the average $\dot{V}O_2$ from 2 minutes 30 seconds to 3 minutes 30 seconds (set 2 to set 3), whereas end exercise values were taken as the average of the last 2 minutes of the tests (29 minutes 0 seconds to 31 minutes 0 seconds/set 20 to set 21).

Mean HS efficiency (HSE) during constant load was expressed in $W \cdot L^{-1} \cdot min^{-1}$, whereas GME was calculated as the ratio of work accomplished per minute (i.e., W in $kcal \cdot min^{-1}$) to energy consumed per minute (i.e., in

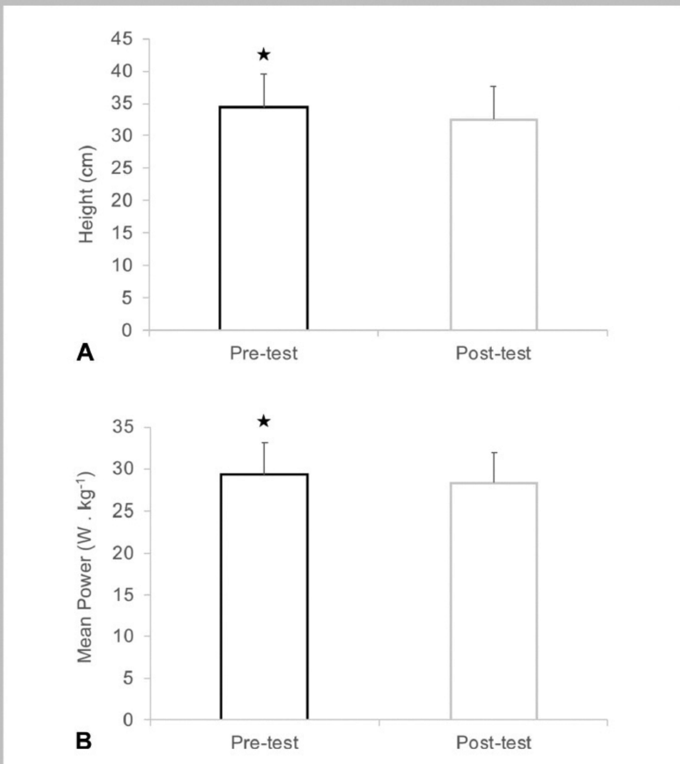

Figure 3. Mechanical fatigue measured as jump height losses (A) and mean power output losses (B) in a countermovement jump test. ★Significant differences vs. post-test ($p < 0.001$).

kcal·min^{-1}), as described elsewhere (8). Energy expenditure was calculated from $\dot{V}O_2$ and the RER using the tables of Lusk (25). To determine the GME and HSE, a linear position transducer, Tendo Weightlifting Analyzer System (Trencin, Slovak Republic) was used to measure bar velocity during constant-load HS exercise testing. The reliability and validity of this device has been previously demonstrated (15). The power output was calculated for each repetition based on bar velocity as follows:

velocity (m·s^{-1}) = vertical movement of the bar (m) × time (s^{-1})

acceleration (m·s^{-2}) = vertical bar velocity (m·s^{-1}) × time (s^{-1})

force (N) = system mass (kg) × [vertical acceleration of the bar (m·s^{-2}) + acceleration due to gravity (m·s^{-2})]

power (W) = vertical force (N) × vertical bar velocity (m·s^{-1}).

The mean power output was calculated as the average of all repetitions.

Lower Limbs Fatigue. Mechanical fatigue was determined using a CMJ test following a method previously described (14). Briefly, the test was performed using a force plate (Quattro Jump model 9290AD; Kistler Instruments, Winterthur, Switzerland) before and after the constant-load HS test at the LT intensity. Pre-test and post-test jumps were exactly performed before starting the HS test (after warm-up) and after the last blood lactate collection, respectively. Participants performed 3 jumps separated by a rest time of 30 seconds, and the mean values of height and mean power recorded in the 3 jumps were used in the subsequent analyses.

Statistical Analyses

The Shapiro-Wilk test was used to check the normal distribution of data, which are provided as mean ± *SD*. Repeated-measures analysis of variance was used to compare $\dot{V}O_2$ kinetics, lactate, EE, GME, and HSE responses. When significant differences emerged, Bonferroni test was used to determine between which checkpoints these occurred. Effect sizes were calculated using partial eta-squared (η_p^2). Statistical power (SP) and intraclass correlation coefficients were also determined.

Pearson product-moment correlation coefficients were calculated to determine a significant relationship between $\dot{V}O_2$ and GME, and between EE and GME. To determine mechanical fatigue, student *t*-test for paired samples was used to evaluate CMJ height and power losses produced in response to the constant-load test at LT intensity. All statistical tests were performed using the software package SPSS Statistics version 23.0 for Mackintosh (SPSS, Chicago, IL, USA). Significance was set at $p < 0.05$.

Results

Descriptive data related to incremental- and constant-load tests are shown in Table 1.

A significant difference in blood lactate levels was observed ($F_{7,\ 126} = 36.51$, $p < 0.001$, $\eta_p^2 = 0.670$, SP = 1), and Bonferroni test confirmed differences between resting and all checkpoints ($p < 0.001$). Although no significant changes ($p > 0.05$) were observed between S3 to S21, a slight rise was detected in the blood lactate kinetics.

The behavior of $\dot{V}O_2$sc kinetics, GME, HSE, and EE during constant-load HS test at LT intensity is shown in Figure 1. A significant $\dot{V}O_2$ increase was detected ($F_{7,\ 126} = 22.09$, $p < 0.001$, $\eta_p^2 = 0.551$, SP = 1), and a slight and sustained increase of the $\dot{V}O_2$sc was observed (Figure 1A). In GME, a significant slight and sustained decrease was observed throughout the constant-load HS test ($F_{6,\ 108} = 10.06$, $p < 0.001$, $\eta_p^2 = 0.359$, SP = 1), and Bonferroni test confirmed changes between S3 and all checkpoints ($p < 0.05$) (Figure 1B). A significant slight and sustained decrease was observed throughout the constant-load test in HSE ($F_{6,\ 108} = 8.56$, $p < 0.001$, $\eta_p^2 = 0.322$, SP = 1), and significance differences were found between S3 and S9, S12, S15, S18, S21 checkpoints ($p < 0.05$) (Figure 1C). A significant slight and sustained increases of EE was identified ($F_{6,\ 108} = 10.54$, $p < 0.001$, $\eta_p^2 = 0.369$, SP = 1), and Bonferroni test determined significant differences between S21 vs. S3, S6, S12, S15 ($p < 0.05$) (Figure 1D).

Significant inverse correlations were found between $\dot{V}O_2$ and GME ($r = -0.93$, $p < 0.001$) (Figure 2A). Significant inverse correlations were detected between EE and GME ($r = -0.94$, $p < 0.001$) (Figure 2B).

Intraclass correlation coefficients were 0.964 (confidence interval [95% CI]: 0.932–0.984) for lactate, 0.973 (95% CI: 0.959–0.988) for $\dot{V}O_2$sc, 0.994 (95% CI: 0.989–0.997) for HSE, and 0.994 (95% CI: 0.990–0.998) for GME.

In response to the constant-load HS test, significant losses were observed in jump height ability ($p < 0.001$) and in mean power output ($p < 0.001$) (Figure 3A, B).

Discussion

The principal finding of this study was that $\dot{V}O_2$sc (small magnitude) and EE tended to rise slowly during constant HS exercise testing conducted at a load intensity equivalent to the LT. In addition, GME and HSE were slightly decreased throughout the HS constant test (Figure 1). Consequently, $\Delta\dot{V}O_2$ and EE were inversely correlated with GME (Figure 2) because the GME was diminishing as $\dot{V}O_2$ and EE were increased throughout the long-term constant-load test.

Although comparable conclusions have been observed in several studies analyzing the relationship between $\dot{V}O_2$ and GME during prolonged constant-load cycling exercise (18), no data are available about the $\dot{V}O_2$sc, EE, HSE, or GME of humans able to sustain 21 sets of 15 repetitions for at least 31 minutes with relatively low circulating lactate levels (~3.3 mMol) in HS exercise.

Our results were slightly higher in absolute values (153.8 ml in 28 minutes vs. 130 ml in 17 minutes) and slightly lower in relative values (5.49 ml·min^{-1} vs. about 8 ml·min^{-1}) than those obtained by professional cyclists (22), although our findings clearly differed from those reported by others (330 ml in 15 minutes or 22 ml·min^{-1}) in nonprofessional cyclists (17), both studies during 20 minutes of constant-load test at 80% of $\dot{V}O_2$max. Carter et al. (6) found that the absolute magnitude of $\dot{V}O_2$sc was significantly higher for cycling than for running at 2 intensities (50%Δ, 334 ± 183 vs. 205 ± 84 ml·min^{-1}; 75%Δ, 430 ± 159 vs. 302 ± 154 ml·min^{-1}). These data verify the assumptions that the precise amplitude of $\dot{V}O_2$sc is influenced by the experimental conditions, characteristics of the participants including fitness and muscle fiber type (2,33), exercise modalities (19), training status (22), and the exercise intensity (5).

Although similar $\dot{V}O_2$sc performance could be observed in different exercise modalities (i.e., HS in our study vs. cycling), the etiology of resistance exercise at LT intensity is uncertain because the power output at LT intensity signifies the highest power output or load that will not induce $\dot{V}O_2$sc intensity (5). In theory, at LT intensity, the $\dot{V}O_2$sc should be nonexistent or very low; however, in our study, a slow rise of $\dot{V}O_2$sc was observed, similar to that reported in professional cyclists at an intensity above LT (80% $\dot{V}O_2$max) (22).

Although our study did not compare HS to cycling exercises, we suspected that HS exercise could induce higher levels of fatigue than cycling at the same relative intensity (LT), elevating the $\dot{V}O_2$sc; this idea is supported by our previous findings (13) that significant losses in jump capacity height and power output production occur only in HS exercise and not in cycling at the end of constant-load testing at LT intensity. Again, this study corroborates a mechanical fatigue (approx. losses of 5% in height and power) induced in lower limbs evaluated by CMJ capacity immediately after constant-load HS exercise test at LT intensity. We suggest a causal relationship between the mechanical mechanisms that induce loss of force in lower extremities and the increased O_2 cost of exercise at the end of constant-load test. The increased $\dot{V}O_2$sc cost of exercise likely appears at intensities at which muscle fatigue has been reported (9). Probably, ATP cost of muscle contraction progressively increased while force production of lower limbs was gradually decreasing (4) throughout the constant-load HS test. Thus, the intensity-dependent decline in muscle efficiency is believed to be associated with the progressive development of muscle fatigue (45).

In addition, Poole et al. (33) proposed that 86% of the $\dot{V}O_2$sc could be determined by an increase in leg oxygen uptake, suggesting that $\dot{V}O_2$sc is mainly activated within the contracting muscle, and the central factors have a minor influence of its amplitude (29). From a mechanical perspective, this means a delayed recruitment of less oxidatively efficient, larger motor units to compensate for attenuated force production in those already active motor units (12), as well as a reduction in the efficiency of skeletal muscle contraction or/and mitochondrial energy production (20). In support of this assumption, the magnitude of $\dot{V}O_2sc$ has been correlated with the percentage (2) and recruitment of type II muscle fibers (37). It has been assumed that the ratio of phosphate produced per oxygen consumed is 18% higher in isolated mitochondria from type I compared with type II muscle, which suggests uncoupling of mitochondrial respiration (44). In this regard, $\dot{V}O_2sc$ reveals a gradual recruitment of type II fibers with exercise duration (33,35), whereas type II fibers are less efficient than type I fibers. The purpose of this study was not to assess the physiological mechanisms responsible for the gradual recruitment of type II fibers; therefore, these assumptions are purely speculative. However, some of these physiological mechanisms may justify the need for recovery time in resistance exercises to continue maintaining a predominantly aerobic metabolism at LT intensity.

The exact mechanisms that cause $\dot{V}O_2sc$ during submaximal intensity exercise are not yet fully understood. We hypothesized that the $\dot{V}O_2sc$ phenomenon might be explained, at least in part, by the change in GME, which estimates the effects of blood alkalinization on the gradual loss of muscle efficiency (12).

Unfortunately, our results cannot be reinforced by previous findings because no data are available about GME and efficiency in resistance exercises during long-term constant-load exercise testing at LT intensity. The GME results reported in this study are higher than those obtained in word class cyclist (23) and professional riders (24) (both ~24%) at the power outputs eliciting the LT and the respiratory compensation point during a ramp test. In well-trained cyclists were observed lower values (~18%) during 2-hour constant-load cycling exercise at 60% of maximal minute power output (18). Other studies in cyclists who were not highly trained (30) have found lower values of GME (~20%) in healthy general population, values of 18–22% have been observed, and values of 16% were reported in chronic patients with severe exercise intolerance during leg cycling exercise (1).

The physiological mechanisms of GME reduction in resistance exercises during constant-load test at LT intensity are fully unknown. The high values found in our study, compared with others, are likely attributable to the characteristics of resistance training. Performing a set of HS or other resistance exercise is usually a brief and intense task in which recovery time is required to execute added series. Probably, making 21 sets of HS exercise causes a relative lack of O_2 supply to muscle loci, further suggesting that a large portion of the energy comes from anaerobic system that could not be determined by measuring metabolic gas exchange. This may have happened from a theoretical perspective because resistance training is chiefly fueled by anaerobic metabolism, generally inducing an important release of anaerobic sources to EE (40) that preclude the use of steady-state $\dot{V}O_2$ to accurately estimate EE (36). As a result, a high-efficiency ratio (work accomplished/EE) could occur.

In addition, Villagra et al. (41) found a higher $\dot{V}O_2$ and a lower GME (approximately 13–20%) as the load increased in 2 forms of squatting exercise. Gross mechanical efficiency differences observed between our results and those of Villagra et al. (41) could be attributed to the experimental protocols used in both studies. Participants in their study performed 24 knee flexions per minute and 96 flexions in 4 minutes with full recovery between sets in 2 forms of squatting exercise. In our study, unlike several studies that used different resistance exercises and protocols (10,38), an experimental protocol of 15 repetitions/30 seconds per set was achieved in which blood lactate levels and $\dot{V}O_2$ responses remained stable during HS constant-load test at LT intensity (13,14). In both studies, light loads were used, and therefore, the differences could be produced by the repetitions/duration established in each set and the type of exercise (HS vs. full squat). In preliminary test, we detected that the blood lactate concentrations and $\dot{V}O_2$ were exponentially increased by rising the repetitions/duration (approximately more than 20 repetitions or 35–40 seconds per series). It can reasonably be expected that if a set of 1 minute in squatting exercises is performed (41), probably, EE will mostly come from anaerobic sources to a greater extent than in our study, triggering a different oxygen consumption and GME. We advocate a protocol of 15 repetitions/30 seconds per set to request mostly aerobic sources in a constant protocol. These postulates should be supported by other experimental designs that analyze the etiology of GME in resistance exercises in both aerobic and anaerobic metabolism.

Significantly higher lactate values were observed during the HS exercise than at baseline, but once they had increased to ~3.3 $mmol \cdot L^{-1}$ at S3, there were no further increases, although GME and HSE were smoothly diminishing as the $\dot{V}O_2$ was slowly rising as the time of the test was extended. Effectively, an inverse relationship between GME and $\Delta\dot{V}O_2$ was observed. It has been reported that a decrease in efficiency coincides with significant increases in oxygen uptake during repeated submaximal exercise (32).

Other possible explanations that would justify the high GME observed could be related to the stretch-shortening cycle in HS exercise. The stretch-shortening cycle involves the active stretching of a muscle (eccentric contraction) followed by its immediate shortening (concentric contraction). Previous findings (41) have demonstrated that the gross, net, and apparent efficiency of rebound squats was significantly greater than that of no rebound squats. The authors concluded that the mechanical work performed in both protocols (rebound vs. no rebound) was the same; however, no rebound exercise induced a greater oxygen cost. It is likely that the rebound HS exercise requires less oxygen due to the contribution of elastic recoil (41). During eccentric phase (prestretching or negative work), a storage of elastic energy in the series elastic components is produced in muscles and tendons. Energy produced is reused during the concentric phase (positive work), possibly decreasing oxygen uptake to a greater extent than resistance exercises with a single concentric phase.

Most of the studies used to evaluate GME have been in cycling test, and cycle pedaling mainly involves concentric muscle actions (11). Various factors affect efficiency and fatigue during exercise, including muscle properties (22), the type of muscle contraction, the type of muscle action, and the exercise methodology (maximal vs. submaximal force generation and duration) (26). Studies comparing GME of the cycle ergometer and resistance exercise are needed to sustain such claims. In addition, differences in power measurement between a linear position transducer and a cycle ergometer should be taken into consideration.

Although GME might be linked to the percent distribution of oxidative, fatigue-resistant (type I) fiber, it certainly is not an accurate measure of muscle efficiency (8). However, GME could be considered as a practical and suitable marker of whole-body efficiency (7), reliable throughout laboratory tests (30), reflecting the ability to perform exercise at the lowest possible metabolic cost.

This study had some limitations that need to be discussed. The 1RM of the subjects could vary from the initial test session to the next; therefore, a test-retest would have been convenient for improving reliable test results by reducing the effects of a systematic bias. This means that the load used (% 1RM) during incremental test session and the power output developed in each repetition of HS exercise could also be slightly altered during the constant-load test at LT intensity.

Future research should be conducted to determine what type of exercises (resistance and/or endurance exercises) could be more efficient to apply both in sports performance and in health-related exercise programs in diverse populations (e.g., healthy adults, sedentary lifestyle, elderly, athletes, diseases, etc.). It would be essential to analyze other resistance exercises (e.g., bench press, leg press, etc.) and compare or combine them with endurance exercises (e.g., cycling, walking, running, etc.) to determine what type of exercises are more suitable for each population according to the objective of the exercise program.

Practical Applications

The etiology of fatigue in resistance exercise is not completely understood. However, better knowledge of the behavior of $\dot{V}O_2$sc, EE, HSE, and GME (typically used in endurance exercises) would allow us to increase performance and discover the potential of resistance exercises in a predominantly aerobic metabolism.

Although no studies have been conducted applying resistance training programs at LT intensity, it is plausible to speculate that resistance training at LT intensity could be a very useful complementary training at a certain time of the season, especially when we refer to fitness training programs and sport performance by improving local muscular resistance and/or cardiorespiratory fitness in both athletes and healthy adults. It is likely that when performing 21 series in resistance exercises with a short recovery time as described in this study, local muscle endurance could be improved using a predominantly aerobic metabolism without producing the metabolites (e.g., H^+) that generate the most purely anaerobic metabolism. It is suspected that, by the decrease in jumping ability, the load used in resistance exercises at LT intensity may be great enough to increase local muscle endurance. In preliminary tests (unpublished data), our research group have observed how the combination of resistance exercises in a circuit training at LT intensity could maintain stable and low blood lactate concentrations, slightly increasing the $\dot{V}O_2$sc and maintaining a high mechanical efficiency. More research is needed to confirm these preliminary findings.

A further possible application could be the prescription of resistance exercises in patients with some sort of disorder. For example, resistance training conducted at an intensity equivalent to the LT would help optimize glucose entry into the muscle, probably improving cardiorespiratory fitness and local muscle endurance.

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The Slow Component of Oxygen Uptake and Efficiency in Resistance Exercises: A Comparison With Endurance Exercises

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Introduction: There is a lack of information regarding the slow component of oxygen uptake (VO_2sc) and efficiency/economy in resistance exercises despite the crucial role played in endurance performance.

Purpose: this study aimed to compare the VO_2sc, efficiency/economy, metabolic, cardiorespiratory responses, rating of perceived effort and mechanical fatigue between cycling and half-squat (HS) exercises during a constant-load test at lactate threshold (LT_1) intensity.

Methods: Twenty-one healthy men were randomly assigned in a crossover design to perform cycle-ergometer or HS tests. The order of the two cycle ergometer tests was an incremental test for determining load-intensity in watts (W) at LT_1, followed by a constant-load test at the LT_1 intensity. For the three HS tests, the order was a 1RM test to determine the load (kg) corresponding to the 1RM percentages to be used during the second test, incremental HS exercise to establish the load (kg) at the LT_1 intensity, and finally, a constant-load HS test at the LT_1 intensity. A rest period of 48 h between each test was established. During the HS and cycle-ergometer constant-load tests, cardiorespiratory and metabolic responses were recorded. Lower limbs fatigue was determined by a jump test before and after the constant-load tests.

Results: A significant exercise mode × time interaction effect was detected in VO_2, heart rate, energy expenditure (EE), gross efficiency (GE), and economy ($p < 0.05$). A significant and sustained VO_2 raise was confirmed in HS exercise ($p < 0.05$) and a steady-state VO_2 was revealed in cycle-ergometer. A higher GE and economy were obtained in HS test than in cycle-ergometer exercise ($p < 0.001$). In both exercises, a non-significant decrease was observed in GE and economy ($p > 0.05$). Lower limbs fatigue was only detected after constant-load HS test.

Conclusion: Although the VO_2, heart rate and EE responses were higher in cycling exercise, the constant-load HS test induced a greater VO_2sc and EE raise than the cycling test in a predominantly aerobic metabolism. These results could explain a decrease observed in jump performance only after HS test. GE and economy could benefit from the eccentric phase of the HS exercise.

Keywords: oxygen uptake kinetics, gross efficiency, energy expenditure, lactate threshold, mechanical fatigue

INTRODUCTION

Laboratory testing of respiratory exchange using a breath-by-breath open-circuit gas analyzer have become a fundamental practice for measuring oxygen uptake (VO_2) kinetics during constant-load endurance exercises. Pulmonary VO_2 tends to rise slowly for a given power output beyond ~3 min during prolonged constant-load endurance exercise, involving sustained lactic acidosis; this surpasses the primary component initiated at exercise onset. This ventilatory phenomenon is known as the slow component of VO_2 (VO_2sc) (Gaesser and Poole, 1996).

As some authors suggest, the VO_2sc could be affected by the behavior of various parameters such as the power-load, VO_2, and lactate threshold (LT), conditioning cardiorespiratory performance and efficiency (Burnley and Jones, 2007). The power output developed above, below or at the LT will determine the amplitude of the VO_2sc response. Therefore, LT intensity plays a key role in the assessment of VO_2sc. According to three-phase model (Skinner and McLellan, 1980), two LTs (LT_1 and LT_2) are recognized during cardiopulmonary exercise testing (Binder et al., 2008). LT_1 is considered as "aerobic threshold" at 40–60% of VO_{2max} (light exercise), and LT_2 is discerned as "anaerobic threshold" at 60–90% of VO_{2max} (moderate to heavy exercise). Obviously, the VO_2sc at LT_2 intensity will increase to a greater extent than at LT_1 intensity during constant-load exercise.

Despite the important role of VO_2sc in endurance performance (Lucía et al., 2002), respiratory exchange tests for evaluating power output or VO_2 at the LT_1 intensity are not usually applied to resistance exercises in laboratory conditions and, therefore, there is a surprising lack information about VO_2sc. To date, only one recent study has focused on VO_2sc in resistance exercises at the LT_1 intensity (Garnacho-Castaño et al., 2018a). Two findings of this study draw the attention. Firstly, the authors reported a slightly higher VO_2sc in absolute values (153.8 $mL.min^{-1}$), during 31 min of constant-load HS testing at the LT_1 intensity in healthy young practitioners, compared to that reported in another study with professional cyclists (130 $mL.min^{-1}$) during 20 min of constant-load test at an intensity above LT_1 (80% VO_{2max}) (Lucía et al., 2000). This detected response of VO_2sc usually occurs at intensities above the LT_1 in endurance exercises (Burnley and Jones, 2007). It could be that the VO_2sc in HS exercise, in a mainly aerobic metabolism (LT_1), is comparable to the VO_2sc observed in endurance exercises at intensities above the LT_1. It has been shown that VO_2sc is lower in a leg cycle compared to an arm crank exercise (Koppo et al., 2002) and higher in cycling than in running exercise (Billat et al., 1998). This difference between the exercise modes was chiefly associated with the amplitude of response (Carter et al., 2000), which in turn was conditioned by loading intensity during constant-load test (Carter et al., 2002). So, the VO_2sc is exercise- and intensity-dependent.

Secondly, the authors demonstrated that the continuous increase in VO_2 and energy expenditure (EE) was linked to a decrease in gross efficiency (GE) (Garnacho-Castaño et al., 2018a). In addition, lower limbs fatigue was detected after constant-load HS test. The VO_2sc could be explained, at least partly, by the variation in GE which assesses the effects of blood alkalinization on the gradual loss of muscle efficiency (Gaesser and Poole, 1996) and progressive fatigue (Garnacho-Castaño et al., 2018a).

Keeping these two premises in mind, it appears reasonable to suggest a greater increase in VO_2sc and EE, whereas the efficiency decrease, during HS exercise than during a constant-load cycling test at the LT_1 intensity. In theory, the power output or load equivalent to the LT_1 intensity means the highest power output or load that will not elicit VO_2sc (Burnley and Jones, 2007) during constant-load endurance tests. However, to the best of our knowledge, no studies have compared VO_2sc, GE, EE, and mechanical fatigue between resistance and endurance exercises during long-term constant-load test at the same aerobic metabolic intensity (LT_1).

To compare VO_2sc and efficiency between resistance and endurance exercises could provide relevant information for clarifying the underlying physiological mechanisms that related VO_2sc and EE to efficiency and fatigue in resistance exercise and, therefore, to determine whether resistance or endurance exercises are more efficient in a predominantly aerobic metabolism. This study aimed to compare VO_2sc, efficiency/economy, metabolic responses and mechanical fatigue between cycling and HS exercises during a constant-load test at an intensity corresponding to LT_1.

MATERIALS AND METHODS

Participants

Twenty-one healthy participants were recruited among the male students of the Physical Activity and Sports Sciences Department (age: 21.4 ± 1.5 years, height: 180.2 ± 5.4 cm, weight: 81.8 ± 8.6 kg, body mass index: 25.2 ± 2.0). All participants had at least 6 months of experience in resistance training and were accustomed to HS exercise.

Four exclusion criteria were established: (1) any cardiovascular, metabolic, neurological, pulmonary or orthopedic disorders that could limit exercise performance,

(2) the use of any medication, supplements, or performance-enhancing drugs, (3) a one-repetition maximum (1 RM) of less than or equal to 150 kg in HS exercise, (4) being an elite athlete.

Eligible participants were informed of the tests they would be taking, and provided their signed written consent to participate. The participants were instructed to refrain from other exercises or resistance training during the course of the study. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Ethics Committee of TecnoCampus-Pompeu Fabra University (Mataró, Barcelona, Spain).

Experimental Design

Subjects were required to visit the laboratory on five occasions at the same time each day under similar environmental conditions (temperature 21–25°C, atmospheric pressure 715–730 mm Hg, relative humidity ∼45%). The protocols were implemented according to the procedures previously established by our research group (Garnacho-Castaño et al., 2015a). Participants were randomly assigned in a crossover design to perform cycle ergometer or HS tests.

The order of the two cycle ergometer tests was an incremental test for determining load-intensity in watts (W) at LT_1, followed by a constant-load test at the LT_1 intensity. For the three HS tests, the order was a 1RM test to determine the load (kg) corresponding to the 1RM percentages to be used during the second test, incremental HS exercise to establish the load (kg) at the LT_1 intensity, and finally, a constant-load HS test at the LT_1 intensity.

A rest period of 48 h between each test was established. During the HS and cycle ergometer constant-load tests, acute cardiorespiratory and metabolic responses were recorded. Timing of blood lactate sampling was the same in both tests. Before and after the constant-load tests, mechanical fatigue in the lower limbs was determined by a counter movement jump (CMJ) test.

Cycle Ergometry Tests

Incremental and constant-load cycle ergometer tests included a 5-min warm-up on a cycle ergometer (Monark ergomedic 828E, Vansbro, Sweden) at an initial pedaling cadence of 50 rev.min^{-1} and work rate of 50 W, followed by 5 min of dynamic joint mobility drills and stretching exercises. After 2-min rest time, the cycle ergometer tests commenced. In both tests, blood lactate concentrations were measured using a portable lactate analyzer (Lactate Pro LT-1710, Arkray Factory Inc., KDK Corporation, Siga, Japan). The reliability of this device has been previously evaluated (McNaughton et al., 2002).

The incremental test was carried out in a ramp protocol starting with a load of 50 W, which was increased in steps of 25 W.min^{-1} until completing 8 min at a pedaling cadence of 50 rev.min^{-1}. Blood samples (5 μL) were attained by finger pricking at rest and every 2 min during the incremental test. The LT_1 was determined according to three-phase model (Skinner and McLellan, 1980), following the guidelines established by Binder et al. (2008). The LT_1 was detected by inspecting blood lactate concentrations plotted against workload according to the protocol described by Weltman et al. (1990). The LT_1 was defined as the highest exercise load completed when a 0.5 mmol.L^{-1} rise over baseline is detected in at least 2 instances.

The constant-load cycle ergometer test involved continuous pedaling at a cadence around 70–80 rev.min^{-1} at an intensity (W) equivalent to the LT_1 previously determined in the incremental test. The test duration was 31 min. Blood lactate samples were obtained at the start of the test and at the following minutes of cycling: min 4, min 8.5, min 13, min 17.5, min 22, min 26.5, and min 31. Respiratory exchange data were recorded during the constant-load test using a breath-by-breath open-circuit gas analyzer (Vmax spectra 29, Sensormedics Corp., Yorba Linda, CA, United States), which had been previously calibrated. VO_2, minute ventilation (VE), carbon dioxide production (VCO_2) and respiratory exchange ratio (RER) were monitored. Heart rate was checked every 5 s by telemetry (RS-800CX, Polar Electro OY, Finland).

Half Squat Tests

In HS tests, a Smith machine (Matrix Fitness, Johnson Health Tech, Cottage Grove, MN, United States) was used to ensure controlled movements. Each HS test started with a warm-up consisting of 5 min of low intensity running and 5 min of joint mobility. This was followed by a specific warm-up consisting of 1 set of 3–5 repetitions (HS) at a relative intensity of 40–60% of the maximum perceived effort. After 2-min, HS test protocols commenced.

Establishing the 1RM involved 3–5 lifting attempts using increasing weight. The 1RM was defined as the last load lifted by the subject, completing a knee extension to the required position. The rest period between each attempt was 4 min (Garnacho-Castaño et al., 2018a).

The incremental HS test was carried out in 5 sets at relative intensities of 10, 20, 25, 30, 35, and 40% 1RM as previously described (de Sousa et al., 2012; Garnacho-Castaño et al., 2015a,b, 2018a). Each set lasted 1 min and involved 30 repetitions of 2 s each (1 s for both eccentric and concentric muscle actions). This rhythm was checked with a metronome while a researcher provided visual and verbal cues. A passive rest period of 2 min between sets (Garnacho-Castaño et al., 2015a,b) was provided while blood samples were collected for LT_1 and the load was augmented. The test was terminated voluntarily by the participant or when he was powerless to continue performing repetitions at the set cadence or did not correctly execute repetitions. Blood samples (5 μL) were obtained by finger pricking 30 s after the end of each set, and lactate levels were measured using the same portable lactate analyzer.

The LT_1 was recognized by means of the algorithm adjustment method based on Orr et al. (1982) as the load-intensity at which blood lactate concentrations start to increase in an exponential manner (Wasserman and McIlroy, 1964). The LT_1 was detected through computerized 2-segment linear regression by fixing the 2 linear regression equations emerging for each segment at the point of intersection between a plot of blood lactate concentration and relative intensity. Data analysis was performed using Matlab version 7.4 (MathWorks, Natick, MA, United States).

The constant-load HS test was conducted as 21 sets of 15 repetitions of 2 s each (1 s for both eccentric and concentric phases) guided by metronome, visual, and verbal cues. The duration of each set was 30 s and the rest period between sets was 1 min. These guidelines were established in preliminary trials and, subsequently, in previous studies (Garnacho-Castaño et al., 2015a,b). In the constant-load test, it was not possible to perform HS sets in a time longer than 30 s. Furthermore, a recovery period of less than 60 s between sets could not be standardized because in both cases the blood lactate concentrations increased exponentially.

The whole constant-load test took 31 min. Respiratory exchange and heart rate data were recorded as previously described (Garnacho-Castaño et al., 2015a,b). Blood samples were obtained at rest and 30 s after the end of the HS sets (S) S3, S6, S9, S12, S15, S18, and S21, when lactate concentrations were obtained as described above for the incremental test.

VO_2 Slow Component, Efficiency/Economy in Constant-Load Tests

In both HS and cycle constant-load tests, the VO_2sc was identified as the difference between end-of-exercise VO_2 and the VO_2 at the end of the third minute of constant-load exercise (Δ VO_2, in $mL.min^{-1}$). The latter was taken as the average VO_2 from 2 min 30 s to 3 min 30 s (set 2 to set 3); end-exercise values were taken as the average of the last 2 min of the tests (29 min 0 s to 31 min 0 s, set 20 to set 21). Mean cycling-(CE) and HS-economy (HSE) was expressed in $W.L^{-1}.min^{-1}$. GE was calculated as the ratio of work accomplished per minute (i.e., W in $kcal.min^{-1}$) to energy consumed per minute (i.e., in $kcal.min^{-1}$) as follows:

$$GE\ (\%) = (\text{Work accomplished}/EE) \times 100.$$

The mean power output during the same period as the respiratory exchange collection was recorded in order to determine "Work accomplished," which was converted into $kcal.min^{-1}$ as follows:

$$\text{Work accomplished}\ (kcal.min^{-1}) = \text{Power output}\ (W) \times 0.01433.$$

Energy expenditure was calculated from VO_2 and the RER. The calorific equivalent of O_2 was determined from the corresponding RER, using the tables provided by Peronnet and Massicotte (1991).

$$EE\ (kcal.min^{-1}) = VO_2\ (L.min^{-1}) \times Kcal.L^{-1}\ \text{of}\ O_2.$$

The power output to quantify HSE and GE during HS test was calculated by means of a reliable and validated linear position transducer (Tendo Weight-lifting Analyzer System, Trenèín, Slovakia) (Garnacho-Castaño et al., 2015c). The power output was computed in each repetition based on bar velocity (Lake et al., 2012). The mean power output was calculated as the mean of all repetitions.

Lower Limbs Mechanical Fatigue

Lower limbs fatigue was evaluated in a CMJ test using a force plate (Quattro Jump model 9290AD; Kistler Instruments, Winterthur, Switzerland), as previously described (Garnacho-Castaño et al., 2015a,b). Jump height, mean power, and peak power were recorded before the start and at the end of both constant-load tests, immediately after the last blood lactate reading. Participants carried out 3 jumps and the mean height, mean power, and peak power output were used in the data analysis. A recovery period of 30 s between each jump was established.

Perceived Effort

The Borg scale was used to monitor the rating of perceived effort (RPE) (Borg, 1978). Scores were recorded by each subject at the blood collection time points for blood lactate determination during incremental and the constant-load tests.

Statistical Analysis

The Shapiro–Wilk test was used to check the normal distribution of data, provided as means, standard deviation (SD), confidence intervals (95% CI) and percentages. To identify significant differences between HS and cycle ergometer exercises in VO_2 kinetics, lactate levels, and economy/efficiency variables during constant-load tests, a general linear model with a two-way analysis of variance (ANOVA) for repeated measures was performed. The two factors were exercise mode (HS and cycle ergometer) and time (corresponding to 7 checkpoints performed in both tests). When appropriate, a Bonferroni *post hoc* adjustment for multiple comparisons was implemented. To determine mechanical fatigue, an ANOVA for repeated measures was performed. A Student's *t*-test was used to compare heart rate, VO_2, RPE and blood lactate concentrations at LT_1 intensity during incremental test in cycle ergometer and HS exercises.

Partial eta-squared (η_p^2) was computed to determine the magnitude of the response to both exercise modes. The statistical power (SP) was also calculated. Intraclass correlation coefficients and coefficients of variation percentage were used to determine

TABLE 1 | Data related to 1RM- and incremental-load tests.

Variables	HS	CYC
1RM (Kg)	200.3 (39.7)	–
HS load at LT_1 (kg)	49.6 (16.2)	–
Relative intensity at LT_1 (%1RM)	23.9 (4.8)	–
Load at LT_1 (W)*	242.6 (86.9)	168.1 (38.2)
VO_2 at LT_1 ($mL.kg^{-1}.min^{-1}$)$^{\delta}$	2.08 (0.32)	1.96 (0.37)
Lactate at LT_1 ($mmol.L^{-1}$)$^{\delta}$	2.51 (0.59)	2.21 (0.51)
HR ($beats.min^{-1}$)$^{\delta}$	134.95 (16.84)	125.43 (17.16)
HR (%)$^{\delta}$	63.14 (8.53)	67.96 (8.60)
RPE (6–20)$^{\delta}$	10.62 (1.80)	9.81 (2.09)

*Data are presented as mean and standard deviation (SD). 1RM, one-repetition maximum; CYC, cycle-ergometer; HR, heart rate; HR (%), percentage regards theoretical maximum heart rate; HS, half-squat; LT_1, lactate threshold one; RPE, rating of perceived exertion; VO_2, oxygen uptake. *Significant differences between HS and cycle ergometer. $^{\delta}$No significant differences between HS and cycle ergometer.*

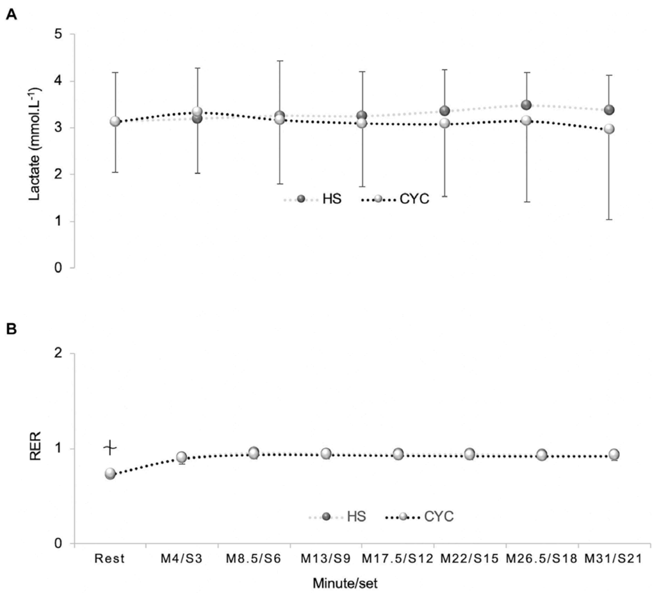

FIGURE 3 | Differences between half-squat (HS) exercise and cycle ergometer (CYC) during constant-load test in: **(A)** Blood lactate. **(B)** Respiratory exchange ratio (RER). No significant differences between cycle ergometer and HS exercises ($p > 0.05$). + Significantly different from M8.5, M13, M17.5, M22, and M26.5 in cycle ergometer ($p < 0.05$) and significantly different from M8.5, M13, and M17.5 in HS exercise ($p < 0.01$).

$\eta_p^2 = 0.49$, SP = 1.00, respectively]. Bonferroni test determined a higher economy in HS than in cycle ergometer exercise ($p < 0.001$). There were significant differences between M4/S3 vs. all checkpoints in both exercises ($p < 0.05$). However, a non-significant but continued decrease was observed from M4/S3 in both exercise modalities ($p > 0.05$) (**Figure 5B**).

Lower Limbs Fatigue

In CMJ test, a significant exercise mode x time interaction effect was observed in jump height [$p = 0.004$, $F_{(1,20)} = 10.76$, $\eta_p^2 = 0.35$, SP = 0.88], mean power [$p = 0.003$, $F_{(1,20)} = 11.82$, $\eta_p^2 = 0.37$, SP = 0.91], and peak power [$p < 0.001$, $F_{(1,20)} = 23.61$, $\eta_p^2 = 0.54$, SP = 0.99]. In Bonferroni test, significant losses were produced between pre- and post-test in jump height ($p < 0.001$), mean power ($p = 0.001$), and peak power ($p < 0.010$) only in HS exercise. Peak power was increased after cycle ergometer test ($p < 0.05$) (**Figure 6**).

DISCUSSION

In support of our initial hypothesis, the main novel finding of this study was that the VO_2sc and EE increased slowly only in HS constant-load test at LT_1 intensity. As expected, during cycle-ergometer exercise at a constant work rate, a steady-state in pulmonary VO_2 and EE was reached. These outcomes could justify, at least in part, a decrease observed in jump performance (height and power) only after HS test. Contrary to our expectation, GE/economy in HS exercise did not reduce to a greater magnitude than in cycle ergometer test at the same LT_1 intensity. In addition, there was a higher response in VO_2 and heart rate during the constant-load test in cycle ergometer than in the HS exercise.

The results of VO_2sc obtained in HS exercise (absolute values 141.4 mL in 28 min, relative values 5.05 mL.min^{-1}) were slightly higher than in the cycling test (absolute values 131.8 mL in 28 min, relative values 4.7 mL.min^{-1}). HS results were reinforced by our previous investigations (Garnacho-Castaño et al., 2018a) that found similar VO_2sc values in HS exercise (absolute values 153.8 mL in 28 min, relative values 5.49 mL.min^{-1}), slightly higher in absolute values (130 mL in 17 min) and slower in relative values (7.6 mL.min^{-1}) than that obtained by professional cyclists at intensities clearly above the LT_1 (80% VO_{2max}) (Lucía et al., 2000). These results visibly differed from those reported in well-trained triathletes during constant work rate at 90% of VO_{2max} in cycling (absolute values 269 mL in 10 min 35 s, relative values ∼25 mL.min^{-1}) and running (absolute values 21 mL in 10 min 54 s, ∼2 mL.min^{-1}) (Billat et al., 1998). These variances

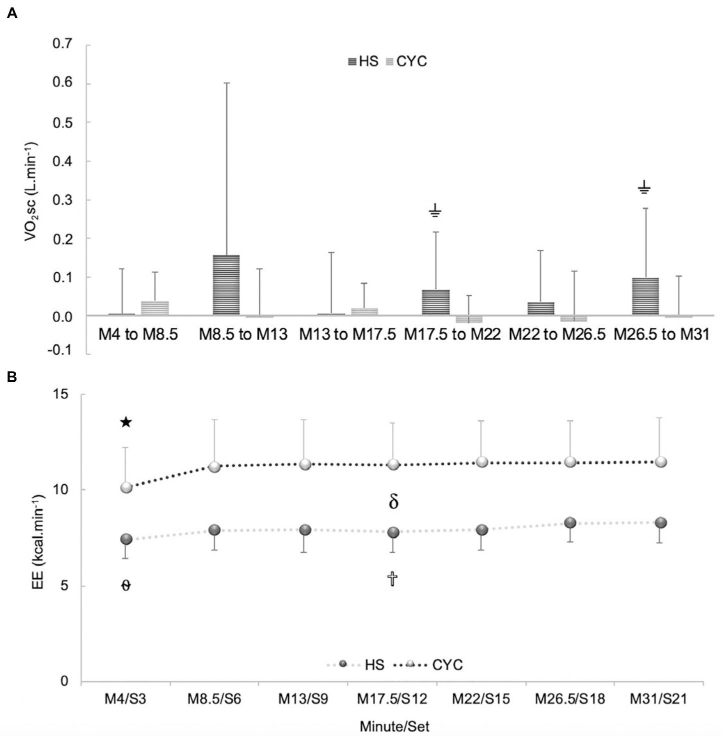

FIGURE 4 | Differences between half-squat (HS) exercise and cycle ergometer (CYC) during constant-load test at each checkpoint: **(A)** Slow component of oxygen uptake (VO_2sc). **(B)** Energy expenditure (EE). ★ Significantly different from M8.5, M13, M17.5, M22, M26.5, and M31 ($p < 0.001$). ϑ Significantly different from S6, S15, S18, and S21. † Significantly different from S21. δ Significant differences between cycle ergometer and HS exercise at each checkpoint ($p < 0.001$). ⏚ Significantly different from cycle ergometer ($p < 0.05$).

of VO_2sc are not fully understood, though they could be related to the difference in the magnitude of VO_2sc between exercise modes and load intensity (Carter et al., 2000; Koppo et al., 2002), training status (Burnley and Jones, 2007), and prolonged constant-load tests (Hopker et al., 2017).

The physiological mechanisms that cause the increase of VO_2sc during constant-load HS test are uncertain because the power output or load equivalent to the LT_1 intensity means, in theory, the highest power output or load that will not elicit VO_2sc (Burnley and Jones, 2007). The VO_2 kinetics observed during constant-load cycling test justified a steady state in VO_2 and EE at the LT_1 intensity. In consequence, the blood lactate increased above the resting values, but did not accumulate over time as occurred during both constant-load tests (Garnacho-Castaño et al., 2015a). If VO_2 continued to increase, especially at the end of the constant-load HS test, it could be assumed that the VO_2sc is associated with fatigue and a decrease in muscular efficiency, so blood lactate should accumulate at a constant or increasing rate in response to the transition toward a predominantly anaerobic metabolism (O'Connell et al., 2017). The only hypothesis that was confirmed was an increase in VO_2sc and EE linked to lower limbs fatigue at the end of the HS test. Blood lactate was oxidized in a mainly aerobic metabolism and exercise intensity was considered as being at or below the anaerobic or LT (Svedahl and MacIntosh, 2003).

This detected response of VO_2sc in HS exercise usually occurs at intensities above the LT_1 in endurance exercises. Unlike the cycle ergometer test, performing 31 min (21 sets) of HS exercise at the LT_1 intensity would only be conceivable with a recovery time between each set. Although break durations of 30 s have indicated negligible effects on lactate kinetics during discontinuous protocols (Gullstrand et al., 1994), our HS protocol caused a relative lack of O_2 supply to muscle loci, further suggesting that an important percentage of the energy

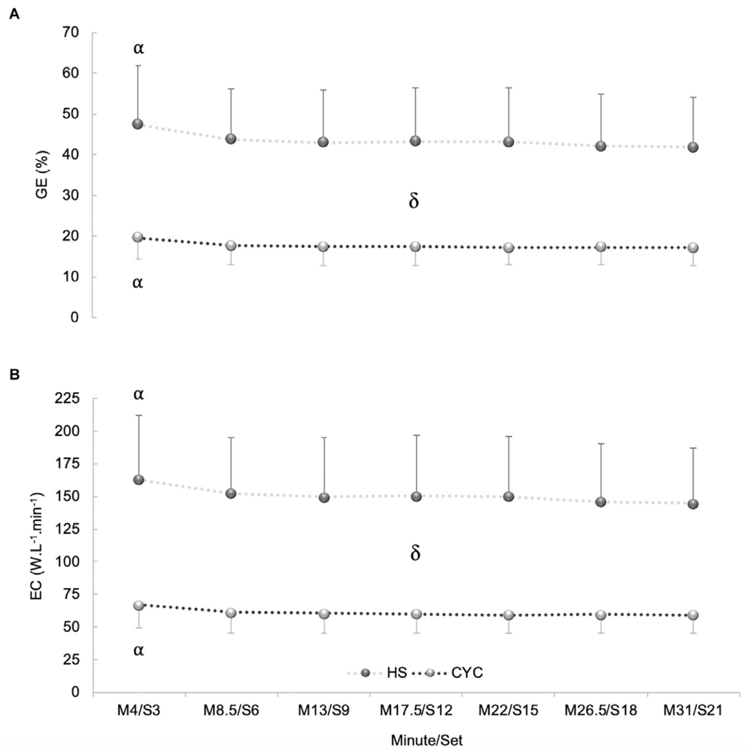

FIGURE 5 | Differences between half-squat (HS) exercise and cycle ergometer (CYC) during constant-load test at each checkpoint: **(A)** Gross efficiency (GE). **(B)** Economy (EC). αSignificantly different from M8.5/S6, M13/S9, M17.5/S12, M22/S15, M26.5/S18, and M31/S21 ($p < 0.05$). δSignificant differences between cycle ergometer and HS exercise at each checkpoint ($p < 0.001$).

derived from anaerobic metabolism might not be quantified by measuring metabolic gas exchange (Garnacho-Castaño et al., 2018a). The HS test probably stimulated a release of anaerobic sources to EE (Tesch et al., 1986) that make it impossible to use steady-state VO_2 to exactly estimate the EE (Scott et al., 2011).

Another feasible mechanism that would help to better understand the etiology of the VO_2sc in resistance exercises links the slight increase in pulmonary VO_2 with the VO_2 rise into the muscle. It has been suggested that increased leg VO_2 could explain for ~85% of the rise in pulmonary VO_2 (Poole et al., 1991). Probably, VO_2sc discovered in HS exercise increased leg VO_2 within the active muscle to a greater magnitude than in the cycle ergometer test and, consequently, EE was augmented only during HS test. The VO_2sc and EE increase would presumably be associated with an increased ATP cost of force production and or increased O_2 cost of ATP resynthesis (Cannon et al., 2014; Korzeniewski and Zoladz, 2015). This energy mechanism would force a delayed recruitment of larger and less efficient motor units from the oxidative point of view to compensate the production of attenuated force in those already active motor units. So, a preferential glycogen depletion of the type I fibers (Vøllestad and Blom, 1985) and the recruitment of type II fibers (Whipp, 1994; Barstow et al., 1996) has been postulated as the most acceptable explanation for the VO_2sc (Gaesser and Poole, 1996).

Glycogen depletion patterns have been detected in type I/II fibers, confirming that both fast-twitch glycolytic muscle fibers and slow-twitch oxidative muscle fibers were activated during high intensity cycling exercise at 80% of VO_{2max}. When cycling exercise was performed at moderate intensity (50% of VO_{2max}), only type I fibers were recruited and no VO_2sc was observed (Krustrup et al., 2004). These findings suggest the recruitment of type I fibers by this mechanism probably occurred during constant-load cycling test. For this reason, VO_2 was not increased and lower limbs fatigue was not induced at the end of

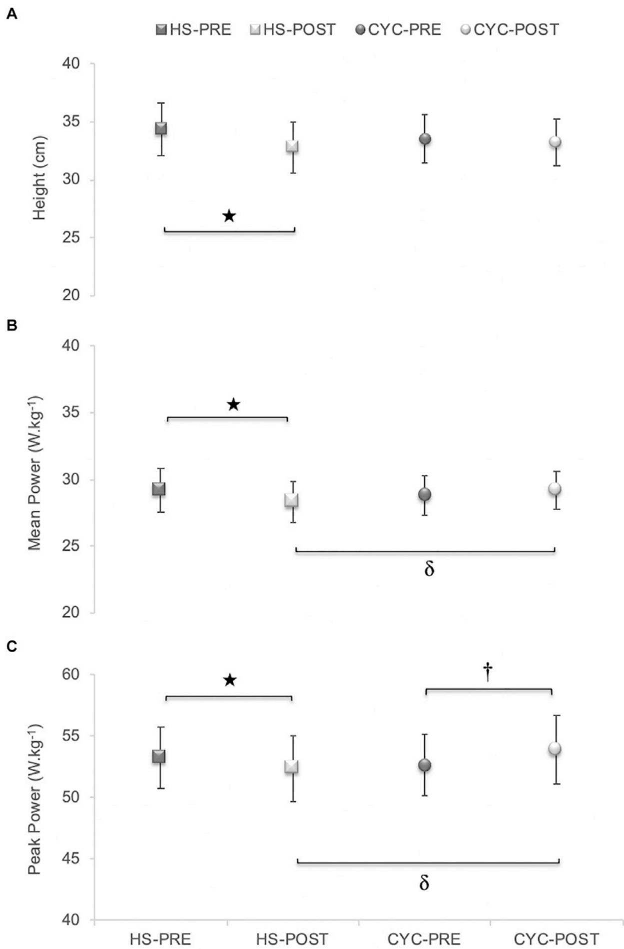

FIGURE 6 | Mechanical fatigue evaluated before and after constant-load exercises using a counter-movement jump test. ★Significant differences between pre- and post-test in HS exercise ($p < 0.01$). †Significant differences between pre- and post-test in cycling exercise ($p = 0.011$). δSignificant differences between cycling and HS tests ($p < 0.05$).

constant-power output cycling. The goal of this study was not to evaluate the gradual fibers-type recruitment associated with the energetic cost; therefore, our arguments are based on findings of others. Nevertheless, it can be assumed that VO$_2$sc and the corresponding increase in EE could be related to progressive fatigue in HS exercise (Garnacho-Castaño et al., 2018a).

In theory, the recruitment forced of type II fibers should induce higher blood lactate concentrations in HS exercise. We suspect that there was no increase in blood lactate levels because a recovery time of 1 min was established between sets. Beneke et al. (2003) demonstrated that repetitive interruptions (90 s after every 5th minute) during 30 min of constant-load testing decreased blood lactate concentrations to a greater extent than without interruptions. During the rest time between sets, the VO$_2$ of the whole body is still raised as a result of elevated post-exercise VO$_2$ while the glycolytic rate of the working muscle mass is diminished. Therefore, the rate of lactate removal is directly linked to VO_2 under the saturation conditions of the substrate.

In addition, the RER was similar and remained stable throughout the constant-load tests despite the VO_2 was higher in the cycle ergometer than HS exercise. The RER during a constant-load test determines the percentage of carbohydrates and fats that are being used as an energy substrate. In endurance exercises have been observed that the fat oxidation is greater during running on treadmill than in the cycle ergometer at the same relative intensity (Achten et al., 2003; Cheneviere et al., 2010). This variance is partly originated by a greater degree of localized intramuscular tension during cycle exercise, which increases the recruitment of fast-twitch motor units (Carter et al., 2000) which mainly depend on carbohydrates as a fuel substrate. As the exercise intensity increases, the change in substrate metabolism toward greater carbohydrates dependence is related to a higher recruitment of the fast-twitch motor units (Coyle, 2000) and the appearance of free fatty acid entrapment (Romijn et al., 1993).

Maybe these physiological mechanisms occurred, at least in part, in the HS exercise. Probably, the HS exercise caused a higher intramuscular tension per muscular unit in the knee extensors than the cycle ergometer, intensified by the negative or eccentric work of the HS exercise. This mechanism might induce a gradual recruitment of less efficient type II muscle fibers as the initially recruited type I fibers become fatigued (Carter et al., 2000). In preliminary tests, we discovered that a recovery time between series equal to or less than 45 s produced an exponential increase in blood lactate levels and relevant muscular fatigue. The rest time of 1 min accumulated between sets throughout the constant-load HS test was a key factor to prevent a greater increase in the carbohydrates and replenish energy substrates and, therefore, for maintaining blood lactate levels in a stable aerobic metabolism.

Although the total time of the tests was the same in both exercises, the real time of execution was 10 min 30 s in HS exercise. The 20 min 30 s of recovery time during HS test could justify, at least in part, that the VO_2 and heart rate was lower in the HS test than cycle ergometer exercise. At the muscular level, probably, the HS exercise was more intense, producing a higher local muscular fatigue. Maybe for this reason, greater fatigue was found in lower limbs after the constant-load HS test. It could be deduced that the muscular fatigue produced in HS exercise stimulated the VO_2sc to a greater extent than the cycle ergometer having a higher cardioventilatory response. Despite these physiological mechanisms, the RPE was the same in both exercises.

In order to explain the VO_2sc phenomenon, GE was compared in both HS and cycling exercises. GE values in the cycle ergometer test were similar to that obtained by well-trained cyclists (∼18%) during long-term constant-load tests at moderate intensity. In HS exercise, we verify our previous findings with GE values of ∼44%. Values of ∼24–26% have been proposed in professional riders at the power outputs eliciting the LT and the respiratory compensation point during a ramp test (Lucía et al., 2002). Other studies have found lower GE values of 14–16% in world-class sprint cross-country skiers (Sandbakk et al., 2010). These values confirm the idea that GE is conditioned by the exercise modality.

According to results obtained in VO_2sc and EE during HS exercise, one could expect to discover a greater GE/economy loss throughout the constant-load HS test. Conversely, a 13% loss (non-significant) in GE was observed in both exercise modalities during constant-load tests. Previous studies have demonstrated that GE continues to diminish during prolonged constant-load tests in cycling (Hopker et al., 2017) and HS exercises (Garnacho-Castaño et al., 2018a) at moderate intensity. We suspect that the higher values and the non-loss of GE throughout the constant-load HS test in comparison with the cycle ergometer test were mainly due to the type of muscular action involved in both exercise modalities. HS execution is characterized by eccentric and concentric muscle actions; cycling prioritizes concentric muscle actions (Ericson et al., 1985). A greater increase in O_2 cost has been shown in no-rebound squats compared to eccentric-concentric squats, and rebound squats stimulate higher efficiency than only concentric squats (Villagra et al., 1993). Pre-stretch allows for storage of elastic energy in the elastic components (muscles and tendons), producing an extra energy that is released during the shortening cycle, probably decreasing O_2 cost. Furthermore, previous studies have demonstrated higher VO_2sc in cycling, compared to running (Carter et al., 2000). The authors speculated that the differences between the two exercise modalities were produced by the greater intramuscular tension induced during heavy cycling exercise and the higher eccentric muscle activity in running. This might cause a relatively lower recruitment of the less efficient type II muscle fibers in running (Carter et al., 2000). The pre-stretch could help to prevent a higher VO_2sc, decreasing O_2 cost and increasing efficiency in HS exercise to a greater extent than concentric pedaling, avoiding a higher recruitment of type II fibers. Furthermore, the eccentric phase has been demonstrated to be a key factor for improving concentric kinetic/kinematic performance during resistance exercises (Garnacho-Castaño et al., 2018b). Our results demonstrated higher power output levels and a lower VO_2 during constant-load HS exercise than in the cycling test. This increased power output contributed to improve GE in HS exercise. In consequence, variances in power output measures between a cycle ergometer and a linear position transducer should be considered.

We think that the muscle mass involved during exercise is another factor to consider. Several studies have shown a slower VO_2sc in running than in cycling (Billat et al., 1998; Carter et al., 2000), or a higher relative increase in VO_2 per unit of time during arm exercise than in a cycling test (Koppo et al., 2002) when a lower muscle mass was involved or when exercise was focused on a specific muscle group. Although the muscle groups involved in HS and cycling exercises are mainly the knee extensors, during HS exercise other muscle groups (i.e., CORE, back, etc.) are likely activated more than in the cycle ergometer exercise. The greater muscle mass involved may help to increase the whole-body efficiency, diminishing O_2 cost.

There are some limitations in this study which should be considered. Eccentric muscle action is linked to significantly higher muscle temperatures than concentric muscle action when both are performed at a comparable power output, rate of oxygen uptake or heat production (Nielsen et al., 1972;

Pahud et al., 1980). This fact may *per se* increase the metabolic rate without any other additional perturbations of the muscular milieu. This increased temperature during negative work in HS exercise could have altered the VO_2 kinetics by accelerating the rate-limiting metabolic reaction connected with oxidative phosphorylation and, moreover, accelerating a greater VO_2 delivery to the capillaries and mitochondria (Koga et al., 1997). It would have been interesting to evaluate how it affects the temperature and the positive (concentric) and negative (eccentric) work at the O_2 cost and consequently to the VO_2sc during constant-load tests.

In addition, the different methodology and protocols applied in both exercises during the incremental tests generates some controversy in the location of the LT_1. This factor could condition the cardioventilatory and metabolic responses during the constant-load tests at LT_1 intensity, producing a bias when comparing both exercises. However, the results reported during the incremental test (**Table 1**) revealed that the detection of the LT_1 in both exercises could occur in an equivalent metabolic instant and a similar exercise intensity. This idea is based on the fact that no significant differences were found in VO_2, heart rate, blood lactate concentrations and RPE between the HS and the cycle ergometer at the LT_1. Our findings are supported by the criteria established in a previous study (Binder et al., 2008). In both exercises, LT_1 occurred at a heart rate of ~65–70% of the maximum heart rate, a rating of perceived exertion of ~10 and a blood lactate concentrations of ~2 mmol.L^{-1}, which is considered as a light intensity according to the criterion defined at the time of the LT_1.

Although it appears that the LT_1 occurred at a similar metabolic moment and intensity during both incremental tests, the cardioventilatory response during the constant-load test at LT_1 intensity was lower in HS exercise. The controversy is now focused on knowing whether both constant-load protocols occurred at the same relative intensity (% VO_{2max}). To solve this problem, both incremental protocols should have been carried out until exhaustion to determine the VO_{2max} and calculate the percentage of VO_2 in both constant-load tests. The response of blood lactate levels and RPE observed throughout the constant-load test determined, at least, a predominantly aerobic metabolic intensity.

Finally, several studies (Carter et al., 2002; Koppo et al., 2002) have compared the ventilatory responses and the VO_2sc between several exercises at the same relative intensity (at, above, below of LT_1). The behavior of VO_2 and VO_2sc is exercise- and intensity-dependent despite they are tested at the same relative or metabolic intensity. Resistance training is typically anaerobic in nature. We think that the most important contribution of this study is that resistance exercises might acquire aerobic metabolic properties selecting a suitable load and manipulating the recovery and execution time of the sets.

CONCLUSION

Although the VO_2 and heart rate responses were higher in cycling exercise, the HS constant-load test induced a greater VO_2sc and EE than the cycling test at the LT_1 intensity. GE could benefit from the eccentric phase of the HS exercise. Resistance training conducted at a load intensity equivalent to a predominantly aerobic metabolism could improve local muscular resistance and whole-body efficiency. Thus, relevant implications for both performance and health exercise programs could be considered. This would allow a faster recovery of the muscle groups from one session to another. In the fitness programs, this methodology would help complement the aerobic endurance training with resistance exercises that involve a greater muscle mass (CORE, upper limbs, stabilizers, etc.) and a higher mechanical efficiency in a metabolism that is primarily aerobic. Future research should focus on continuous protocols (without rest periods) as in endurance exercise, combining resistance exercises in the form of circuit training. This scientific knowledge could be an important advance in the assessment of resistance exercises for sports performance and health promotion.

DATA AVAILABILITY

All datasets generated for this study are included in the manuscript and/or the supplementary files.

AUTHOR CONTRIBUTIONS

JM-M and MG-C conceived and designed the research. All authors performed the test protocols and edited, revised, and approved the final version of the article. MG-C and JM-M analyzed the data. LA-A, NS-P, MB, RF-R, LC, and EC contributed reagents, materials, and analysis tools. LA-A, JM-M, RF-R, and MG-C prepared the figures and drafted the article.

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PLOS ONE

RESEARCH ARTICLE

Ventilatory efficiency during constant-load test at lactate threshold intensity: Endurance versus resistance exercises

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Abstract

There is a lack of evidence about the ventilatory efficiency in resistance exercises despite the key role played in endurance exercises. This study aimed to compare the cardiorespiratory, metabolic responses and ventilatory efficiency between half-squat (HS) and cycle ergometer exercises during a constant-load test at the lactate threshold (LT) intensity. Eighteen healthy male participants were randomly assigned in a crossover design to carry out HS or cycle ergometer tests. For the three HS tests, a one repetition maximum (1RM) test was performed first to determine the load (kg) corresponding to the 1RM percentages. In the second test, the incremental HS exercise was carried out to establish the load (kg) at the LT intensity. Finally, a constant-load HS test was performed at the LT intensity. The first cycle ergometer test was incremental loading to determine the intensity in watts corresponding to the LT, followed by a constant-load test at the LT intensity. A recovery time of 48 hours between each test was established. During both constant-load test, cardiorespiratory and metabolic responses were monitored. A significant exercise mode x time interaction effect was only detected in oxygen uptake (VO_2), heart rate, and blood lactate ($p < 0.001$). No differences were found between the two types of exercise in ventilatory efficiency ($p > 0.05$). Ventilation (VE) and carbon dioxide were highly correlated ($p < 0.001$) in the cycle ergometer ($r = 0.892$) and HS ($r = 0.915$) exercises. In the VO_2 efficiency slope (OUES), similarly significant and high correlations ($p < 0.001$) were found between VO_2 and $\log_{10}$ VE in the cycle ergometer ($r = 0.875$) and in the HS ($r = 0.853$) exercise. Although the cardioventilatory responses were greater in the cycle ergometer test as compared to HS exercise, ventilatory efficiency was very similar between the two exercise modalities in a predominantly aerobic metabolism.

Introduction

Recent studies have used the lactate threshold (LT) or the ventilatory threshold as parameters to monitor and assess cardiorespiratory responses [1, 2, 3], slow component of oxygen uptake, and gross mechanical efficiency [4] in unusual resistance exercises using a cardiopulmonary exercise tests (CPET), as also occurs in endurance exercise [5–9]. During constant-load test at a load intensity equivalent to the LT, it was observed a greater cardiorespiratory response to cycle ergometer exercise compared to the half-squat (HS). The cardiorespiratory and metabolic response was stable in both types of exercise; greater muscular fatigue was observed after completion of the HS test [2]. As could be expected, resistance exercises increased local muscular fatigue in the lower limbs, while endurance exercises increased cardiorespiratory response.

Cardiorespiratory fitness is frequently evaluated by means of ventilatory efficiency [10, 11]. The fundamental cause of ventilatory efficiency is the matching of ventilation (VE) and perfusion in the lungs. The mismatching of perfusion and VE diminishes the efficiency of lung gas exchange, demanding an increase in VE for a given CO_2 output and arterial PCO_2. This mismatching phenomenon contributes essentially to hyperpnea and dyspnea [12] affecting ventilatory performance. It is common to assess ventilatory efficiency in endurance exercises mostly in different types of diseases or pathologies [13–14], in sports performance [11], and in healthy subjects [10, 15], establishing the slope of the linear relationship between VE and carbon dioxide (VE/VCO_2 slope) during an incremental test up to the anaerobic [16] or ventilatory threshold [17] and the ventilatory compensation point [10]. Another option to quantify ventilatory efficiency in endurance exercises is to determine the oxygen uptake efficiency slope (OUES). The OUES indicates how effectively oxygen is extracted and taken into the body during incremental exercise [17]. The OUES is considered a very appropriate tool in the evaluation of cardiovascular fitness in overweight adolescents [18], the severity of heart disease [19], the effects of physical training or treatment [20, 21], and the risk of a serious or fatal event [22].

Although many studies have analyzed the slope of VE/VCO_2 and OUES by age, sex, fitness level, and diseases in endurance exercises [10, 11, 14, 17, 19], it is unusual to observe studies comparing VE/VCO_2 slope and OUES between different exercise modalities [23, 24]. Sun et al. [10] demonstrated that VE/VCO_2 slope is not exercise mode-dependent, however, Davis et al. detected that VE/VCO_2 slope was lower on the cycle ergometer than the treadmill in women but not in men [25]. For OUES, treadmill values were higher than cycle ergometer [24]. Recently, Salazar-Martinez et al. demonstrated that ventilatory efficiency was unaffected by ergometer type [26]. The assumption that ventilatory efficiency could be similar between different exercise modalities is controversial and more research is needed to compare several exercise modes. Despite the importance that has been given in the scientific literature to the assessment of ventilatory efficiency in endurance exercises in healthy people and especially in the clinical settings, it is a field of knowledge that needs to be explored in resistance exercises. There are no previous data regarding VE/VCO_2 slope and OUES in HS exercise and, to the best of our knowledge, ventilatory efficiency has not been compared between resistance and endurance exercises.

In cardiorespiratory fitness assessment, this knowledge could have an added value in selecting the type of exercise to improve ventilation efficiency. If resistance exercises demonstrate adequate ventilatory efficiency, professionals in the health field could use resistance training to increase local muscle endurance while maintaining good ventilatory efficiency.

It is common to assess ventilatory efficiency during incremental endurance tests, however, prolonged constant-load endurance tests can be recommended as a good option in the clinical health setting to determine the VE/VCO_2 slope [27, 28] or OUES because they do not subject the participants to significant cardiorespiratory, metabolic, and muscular stress. A constant-load test at LT intensity might be an interesting alternative for applying to healthy people in both endurance and resistance exercises to assess ventilatory efficiency without inducing a strenuous cardiorespiratory and metabolic stress.

The main objective of this study was to compare the ventilatory efficiency, measured by OUES and VE/VCO_2 slope, and cardioventilatory responses of HS and cycle ergometer exercise in a constant-load test at LT intensity. A secondary goal was to determine the relationship between the OUES and the VE/VCO_2 slope in both exercise modalities in each participant.

Material and methods

Participants

Eighteen healthy male participants were recruited among the students of the Department of Physical Activity and Sports Sciences (age: 21.8 ± 1.5 years, height: 180.3 ± 5.7 cm, weight: 82.6 ± 9.0 kg, body mass index: 25.4 ± 2.0). All participants had at least 6 months of resistance training experience and were completely familiar with the HS exercise and the cycle ergometer.

Four exclusion criteria were established: 1) any cardiovascular, metabolic, neurological, pulmonary, or orthopedic disorder that could limit exercise performance, 2) the use of any medication, supplements, or substance that could improve performance, 3) 1RM $\leq$150 kg in the exercise of the HS, 4) elite athlete status.

Eligible participants were informed of the tests to be performed and those who agreed with the study protocols signed their written consent to participate. The subjects were instructed to abstain from other exercise or training during the two-week study period. The study protocol adhered to the principles of the Declaration of Helsinki for studies with human beings and was approved by the Ethics Committee of the Alfonso X El Sabio University (Villanueva de la Cañada, Madrid, Spain).

Experimental design

The participants visited the Exercise Physiology Laboratory five times during the two-week study period, at the same time of day (± 2 hours) and in similar environmental conditions (room temperature 21–25˚C, atmospheric pressure 715–730 mm Hg, relative humidity ~ 45%). Participants were randomly assigned in a crossover design to perform HS or cycle ergometer tests. A rest period of 48 hours was established between each of the five tests. The protocols were implemented according to procedures previously established by our research group [2].

For the three HS tests, a one repetition maximum (1RM) test was performed first to determine the load (kg) corresponding to the 1RM percentages to be used during the second test, the incremental HS exercise to establish the load (kg) at the intensity corresponding to the LT. Finally, a constant-load HS test was performed at the LT intensity established during the incremental exercise test. The first cycle ergometer test was incremental loading to determine the intensity in watts (W) corresponding to the LT, followed by a constant load test at the LT intensity. During both constant-load test, acute cardiorespiratory and metabolic responses were monitored. The timing of the blood lactate sampling was the same for both the HS and cycle ergometer testing.

Half squat tests

In the HS tests, a Smith machine (Matrix Fitness, Johnson Health Tech, Cottage Grove, MN, USA) was used to ensure safe and controlled movements. HS technique was determined as in previous studies [3, 29]. The variation in range of motion (ROM) during HS exercise was accurately determined during a familiarization session and in all the tests. Participants positioned themselves under the barbell in an upright position with the knees and hips fully extended and legs spread approximately at the shoulders' width. The barbell was placed on the upper back (trapezius muscle), approximately at the level of the acromion. During the descent of the bar, participants flexed the knees and hips (eccentric action) to lower the barbell in a controlled manner, until 90^0 flexion of the knees [30]. From this position, the concentric muscle action was started until fully extending the knees and hips. The body position was individually adjusted and exactly replicated on each HS test.

Each HS test started with a 5-minute low-intensity general run and 5-minute general joint mobility warm-up, followed by a specific warm-up of a series of 3–5 repetitions (HS) at a relative intensity of 40–60% of 1RM.

1RM test. After a 2-minute rest, the HS test protocols began. To determine 1RM, 3–5 series were carried out, using an increasing weight each time. The 1RM was defined as the last load lifted by the subject, completing a knee extension to the required position. The rest period between each attempt was 4 minutes.

Incremental HS test. The incremental HS test was carried out in 6 one-minute series, at relative intensities of 10%, 20%, 25%, 30%, 35%, and 40% 1RM as described in previous studies [2, 4, 29]. In each series, 30 repetitions of 2 seconds each were performed (1 second for eccentric muscle action and 1 second for concentric action), using a metronome to establish the rhythm; a member of the research team provided visual and verbal cues to maintain an adequate rate. A passive rest period of 2 minutes between series was established. During this period, blood samples were collected by an experienced researcher and the corresponding load was increased. The test ended when the repetitions were no longer executed correctly or was voluntarily terminated by the participant when he could not perform the repetitions at the established cadence. Blood samples (5 μL) were obtained by pricking the finger 30 seconds after the end of each series. Lactate levels were measured using a portable analyzer (Lactate Pro LT-1710, Arkray Factory Inc., KDK Corporation, Siga, Japan).

Based on the algorithmic adjustment method described by Orr et al. [31], LT was defined as the load intensity at which blood lactate concentrations begin to increase exponentially [32]. LT was detected by two-segment linear regression, placing the 2 emergent linear regression equations for each segment at the point of intersection between a plot of blood lactate concentration and relative intensity [33]. Data analysis was done using Matlab version 7.4 (MathWorks, Natick, MA, USA).

Constant-load HS test. In the constant load HS test, 21 sets of 15 repetitions were performed. The duration of each set was 30 seconds (1 second each for the eccentric and concentric phases, guided by a metronome and visual and verbal signals), with 1-minute rest between sets. The entire constant-load test lasted 31 minutes. Respiratory exchange data were recorded during the constant-load test using a breath-by-breath open-loop gas analyzer (Vmax spectra 29, Sensormedics Corp., Yorba Linda, California, USA), previously calibrated. VO_2, VE, VCO_2, and respiratory exchange ratio (RER) were monitored. The heart rate was quantified every 5 seconds by telemetry (RS-800CX, Polar Electro OY, Finland). To determine lactate concentrations, finger-prick blood samples were obtained, as described for the incremental test, at rest and 30 seconds after the end of 7 HS sets (S): S3, S6, S9, S12, S15, S18 and S21.

Cycle ergometer tests

The incremental and constant-load tests on a cycle ergometer (Monark ergomedic 828E, Vansbro, Sweden) included a 5-minute warm-up at a pedaling rate of 50 rev.min^{-1} and a load of 50 W, followed by 5 minutes of dynamic joint mobility and stretching exercises. The load during the incremental and constant-load tests was defined according to the characteristics of the cycle ergometer, as previously described [34]. Briefly, pedaling at an intensity of 50 W is the same as pedaling at a rate of 50 $rev.min^{-1}$ at a load of 1-kilogram force (kgf). To increase the load by 25 W during an incremental protocol, pedaling cadence at a rate of 50 $rev.min^{-1}$ should be performed at a load equivalent to 0.5 kfg. After 2 minutes of rest, the specific tests on the cycle ergometer began.

Incremental cycle ergometer test. The incremental test using a ramp protocol that started with a load of 50 W (50 $rev.min^{-1}$ at a load of 1kgf), increased in steps of 25 $W.min^{-1}$ until completion of 8 min at a pedaling rate of 50 $rev.min^{-1}$ at a load of 0.5 kgf. Blood samples (5 μL) were obtained by finger pricking at rest and every 2 minutes during the incremental test. The LT was detected by inspecting the plot of blood lactate concentrations against the workload, according to the protocol described by Weltman et al. [35]. LT was defined as the highest exercise load completed when an increase of 0.5 $mmol.L^{-1}$ was detected over baseline concentrations in at least 2 consecutive samples.

Constant-load cycle ergometer test. The constant load cycle ergometer test was performed with continuous pedaling at a rate between 70–80 $rev.min^{-1}$ at an intensity (W) equivalent to the LT, previously determined in the incremental test. The load in kfg was individually adjusted to each subject at 70–80 $rev.min^{-1}$ to develop the W corresponding to the LT intensity. Total duration of the test was 31 minutes. The blood lactate samples were obtained with the same portable analyzer as in the HS test, at the beginning of the test and (coinciding with the timing in the HS test) at the following minutes (M) thereafter: M4, M8.5, M13, M17.5, M22, M26.5, M31. During the constant-load test, respiratory exchange and heart rate data were recorded as described in the HS constant-load test.

Ventilatory efficiency

The ventilatory efficiency of each participant was determined in two ways: 1) the slope of the relationship between VE and VCO_2 during each constant-load test; 2) the OUES slope, calculated as the relationship between VO_2 and the logarithm of the VE during the constant-load test: VO_2 = a log10 VE + b).

Statistical analysis

The Shapiro-Wilk test was used to verify the normal distribution of the data, reported as mean, standard deviation (SD), and confidence intervals (95% CI). To identify significant differences between the HS and cycle ergometer exercises in the cardioventilatory and lactate variables, a general linear model was performed with a two-way analysis of variance (ANOVA) for repeated measurements. The two factors were the exercise mode (HS or cycle ergometer) and time point (corresponding to 7 control points in both exercise modes). When appropriate, a post-hoc Bonferroni adjustment was implemented for multiple comparisons. To determine the differences between the two exercise modes in the VE/VCO_2 and OUES slopes, Student-t was applied for related samples. The slope of VE/VCO_2 and OUES was calculated by linear regression between VE and VCO_2 and between VO_2 and log10 VE, respectively. The Pearson product-moment correlation coefficients were calculated to determine significant relationships between the VE and the VCO_2 and between the VO_2 and the log10 VE, and to establish the possible relationship between the OUES and the VE/VCO_2 slope.

Partial eta square (η_p^2) was calculated to determine the magnitude of the response in ANOVA analysis. Cohen´s *d* for the planned comparisons was used to determine effect sizes. A large effect size was defined as $\eta_p^2 \geq 0.26$, $d \geq 0.80$; moderate $\eta_p^2 \geq 0.13$, $d \geq 0.40$; and small $\eta_p^2 < 0.02$, $d < 0.40$ [36]. Statistical power (SP) was also determined. The intraclass correlation coefficients and the percentage of variation coefficients were calculated to determine the relative and absolute reliability. The level of significance was set at $p < 0.05$. All statistical methods were performed using the SPSS Statistics software package version 23.0 for Macintosh (SPSS, Chicago, IL, USA). The graphics were made in the Microsoft Excel version 16.20 for Mac.

Results

Anthropometric characteristics and incremental test data for the HS and cycle ergometer exercises are shown in Table 1.

Differences in cardioventilatory and lactate responses are shown in Table 2. The mean of the intraclass correlation coefficients and the coefficients of variation for cardioventilatory variables and lactate were 0.970 (0.942–0.987) and 6.7% ± 3.4%, respectively.

For absolute VO_2, a significant exercise mode x time interaction effect was observed ($p = 0.007$, $F_{(6, 102)} = 3.18$). Bonferroni test confirmed that VO_2 was significantly higher in cycle ergometer than HS exercise at the 7 established control points ($p < 0.001$; large effect $d \geq 1.64$). In cycle ergometer, a significant lower VO_2 was detected in M4 regarding the rest of the control points ($p \leq 0.002$; moderate effect $d \geq 0.46$ and ≤ 0.60). However, a VO_2 stabilization was observed after M8.5 ($p > 0.05$). In HS exercise, a significant increase in VO_2 was observed ($p < 0.05$) in S3 with respect to S6 (moderate effect, $d = 0.46$), S18 (large effect, $d = 0.95$), and S21 (large effect, $d = 0.86$) (Fig 1A).

No significant exercise mode x time interaction effect was found for the relative VO_2 ($p > 0.05$) and VE variable ($p > 0.05$).

For heart rate, a significant effect ($p < 0.001$) was observed for exercise mode x time interaction ($F_{(6, 102)} = 5.85$). The Bonferroni test determined that heart rate was significantly lower in HS exercise than in cycle ergometer test at the 7 established control points ($p < 0.05$; in M4/S3, moderate effect $d = 0.49$; rest of control points large effect $d \geq 0.94$). In cycle ergometer exercise, a significant increase in heart rate was confirmed in M4 regarding all control points ($p < 0.01$; moderate effect versus M8.5 and M13, $d \geq 0.62$ and ≤ 0.74; large effect versus M17.5, M22, M26.5, M31, $d \geq 0.83$) (Fig 1B).

Blood lactate concentrations indicated a significant exercise mode x time interaction ($p < 0.001$, $F_{(7, 119)} = 6.93$). The Bonferroni adjustments showed a significant increase from rest period in both exercise modes ($p \leq 0.005$; large effect $d \geq 1.71$). Significant higher blood

Table 1. Descriptive data related to anthropometric characteristics, 1RM- and incremental-load tests.

Variables	Mean (SD)
Participants	N = 18
Age (years)	21.2 (1.5)
Height (cm)	180.3 (5.7)
Weight (kg)	82.6 (9.0)
BMI ($kg.m^{-2}$)	25.4 (2.1)
1RM in HS (kg)	206.3 (36.4)
HS load at LT (kg)	51.2 (9.0)
HS relative intensity at LT (%)	25.8 (4.6)
CYC load at LT (W)	130.8 (24.8)

Abbreviations: 1RM = one-repetition maximum; BMI: body mass index; CYC: cycle-ergometer; HS = half-squat; LT = lactate threshold; SD = standard deviation.

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Table 2. Differences in cardioventilatory and lactate responses between half-squat vs cycle-ergometer during constant-load test at lactate threshold intensity.

	CYC (95% CI)	HS (95% CI)	P^1 ES/SP	P^2 ES/SP	P^3 ES/SP
VO_2 (L.min^{-1})	2.2	1.6	0.007	< 0.001	< 0.001
	(2.0–2.5)	(1.5–1.7)	0.2/0.9	0.6/1.0	0.6/1.0
VO_2 (mL.kg^{-1}.min^{-1})	19.8	27.8	0.517	< 0.001	< 0.001
	(18.6–20.9)	(24.8–30.8)	(0.1–0.3)	(0.2–1.0)	(0.6–1.0)
VCO_2 (L.min^{-1})	2.1	1.5	0.062	< 0.001	< 0.001
	(1.8–2.3)	(1.4–1.6)	0.1/0.7	0.6/1.0	0.6/1.0
VE (L.min^{-1})	53.7	43.1	0.510	< 0.001	0.002
	(48.2–59.2)	(40.1–46.1)	0.1/0.3	0.4/1.0	0.5/0.9
RER	0.9	0.9	0.923	< 0.001	0.084
	(0.9–0.9)	(0.9–1.0)	0.0/0.1	0.5/1.0	0.2/0.4
HR (beat.min^{-1})	139.6	123.8	< 0.001	< 0.001	< 0.001
	(131.2–148.0)	(116.7–130.8)	0.3/1.0	0.6/1.0	0.6/1.0
Lactate (mmol.L^{-1})	2.6	2.8	< 0.001	< 0.001	0.148
	(2.2–2.9)	(2.6–3.1)	0.3/1.0	0.8/1.0	0.1/0.3

Abbreviations used: CYC: cycle-ergometer; ES: effect size; HR: heart rate; HS: half-squat; L: liter; min: minute; RER: respiratory exchange ratio; SP: statistical power; VCO_2: carbon dioxide production; VE: minute ventilation; VO_2: oxygen uptake. P^1 Significant differences for exercise mode x time interaction effect. P^2 Significant differences for time effect. P^3 Significant differences for exercise mode effect. Data are provided as mean and 95% confidence intervals (95% CI).

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lactate levels were found in HS exercise regarding cycle ergometer ($p < 0.05$) at control points M22/S15 (moderate effect, $d = 0.72$), M26.5/S18 (large effect, $d = 0.82$), and M31/S21 (large effect, $d = 1.19$) (Fig 2).

In the RER, no significant interaction effect was observed for exercise mode x time ($p > 0.05$).

Regarding VE/VCO_2 slope and OUES, no differences were found between the two types of exercise ($p > 0.05$) (Fig 3).

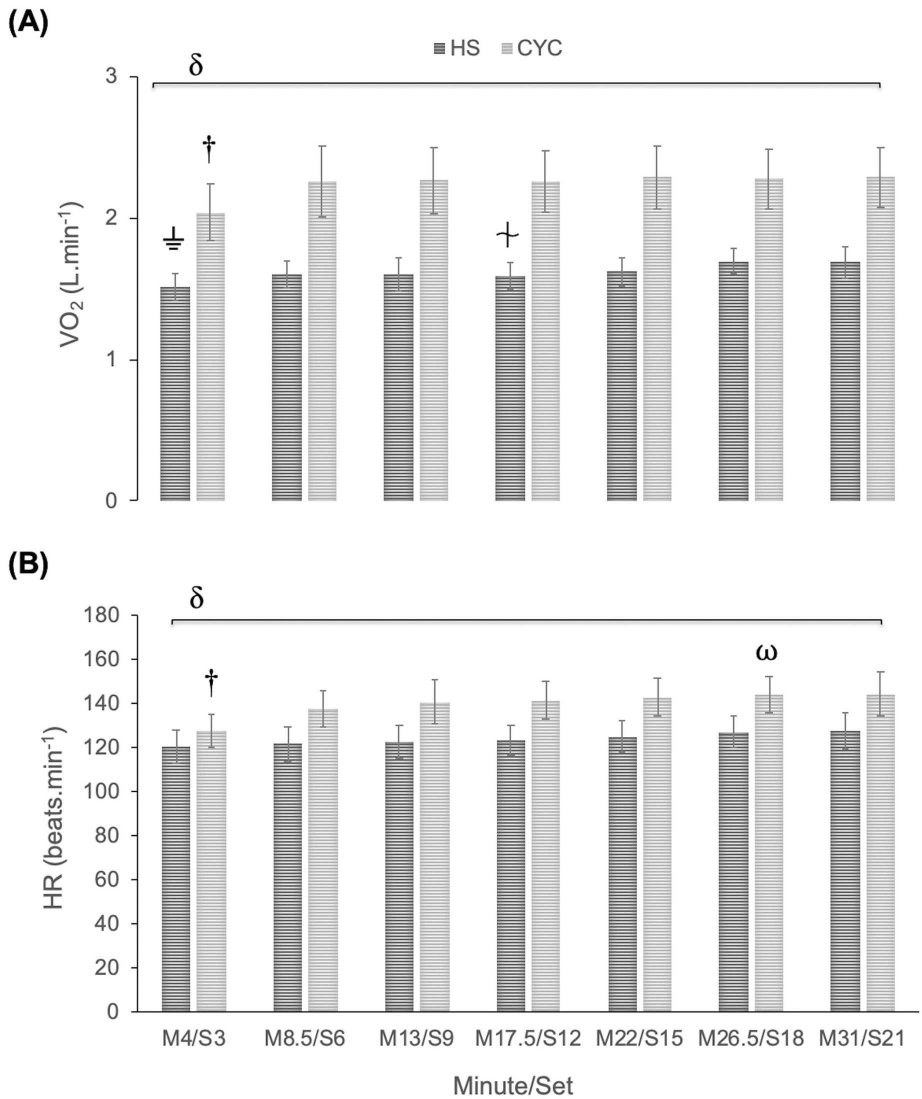
In the VE/VCO_2 slope, VE and VCO_2 were highly correlated ($p < 0.001$), both in the cycle ergometer ($r = 0.892$) and HS ($r = 0.915$) modalities (Fig 4A and 4B, respectively).

In the OUES, similarly high correlations ($p < 0.001$) were found between VO_2 and $\log_{10}$ VE in the cycle ergometer ($r = 0.875$) and in the HS ($r = 0.853$) (Fig 5A and 5B, respectively).

No significant correlation was found between the OUES and the slope of the VE/VCO_2 in the HS ($r = -0.345$, $p = 0.160$) nor in the cycle ergometer ($r = 0.315$, $p = 0.203$). Also, no significant correlation was observed between the HS and cycle ergometer modes in OUES ($r = 0.356$, $p = 0.147$) or VE/VCO_2 slope ($r = 0.422$, $p = 0.081$).

Discussion

To the best of our knowledge, this study applied two novelties in methodological approach, with respect to previous research. First, it determined ventilatory efficiency in HS exercise by two distinct methods (VE/VCO_2 slope and OUES); second, it compared HS and cycle ergometer ventilatory efficiency in constant-load tests conducted at an intensity equivalent to the LT. Although the cardioventilatory responses were greater in the cycle ergometer test as compared to HS, ventilatory efficiency was very similar between the two exercise modalities. In addition, the blood lactate concentrations were similar between both exercise modes although these values were slightly higher in HS exercise than in the cycle ergometer exercise at the end of the constant-load tests.


(A)
HS
CYC
δ
†
VO2 (L.min-1)
3
2
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(B)
δ
ω
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HR (beats.min-1)
180
160
140
120
100
80
60
40
20
0
M4/S3
M8.5/S6
M13/S9
M17.5/S12
M22/S15
M26.5/S18
M31/S21
Minute/Set

Fig 1. Multiple comparisons between cycle ergometer (CYC) and half-squat (HS): (A) Oxygen uptake (VO_2). (B) Heart rate (HR). δ Significant differences $p < 0.05$ between cycle ergometer and half-squat at each checkpoint. † Significantly different from M8.5, M13, M17.5, M22, M26.5, M31 in cycle ergometer, $p < 0.01$. ω Significantly different from M8.5, M17.5 in cycle ergometer, $p = 0.017$. ⏚ Significantly different from S6, S18, S21 in HS exercise, $p < 0.05$. ∔ Significantly different from S21 in HS exercise, $p = 0.026$.

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These findings replicated the results obtained in previous investigations, in which the cardiorespiratory responses were higher in the cycle ergometer test than in HS exercise [2]. The constant-load HS test at LT intensity likely induced a lower cardioventilatory response because a rest time was implemented between sets. To date, it has been unfeasible to perform a continuous protocol in the HS exercise at the LT intensity. In theory, a continuous HS protocol would increase intramuscular pressure leading to augmented muscle tension and progressive fatigue. These physiological mechanisms would produce the collapse of capillaries and diminish the oxygen available into the muscle and thus increasing the blood lactate levels [37]. Although it is usual to find a different cardiorespiratory response between several endurance exercise modalities at the same relative intensity [38], the available studies comparing resistance versus endurance exercises during constant-load test at LT intensity are currently insufficient to draw more precise conclusions.

The VE/VCO_2 slope and OUES results obtained in both exercises are considered normal and comparable to other studies with healthy adults (19–30 in VE/VCO_2 slope, 2.55 ± 1.01 n = 417 in OUES) [10, 16, 24]. In elite youth cyclists [11], the slope of the VE/VCO_2 was similar (about 28) to our study, but the OUES was higher: 3.8 vs. 2.5 in our study. The difference could be due to the novel methodology used in our study and the greater cardiorespiratory fitness of elite youth cyclists. No studies are available for comparison of the VE/VCO_2 slope, cycle ergometer values, or HS data in a constant-load test at LT intensity. However, our results on ventilatory efficiency were very similar to those obtained in other studies in endurance exercises (cycling) at the intensity of the anaerobic threshold [11], perhaps because both

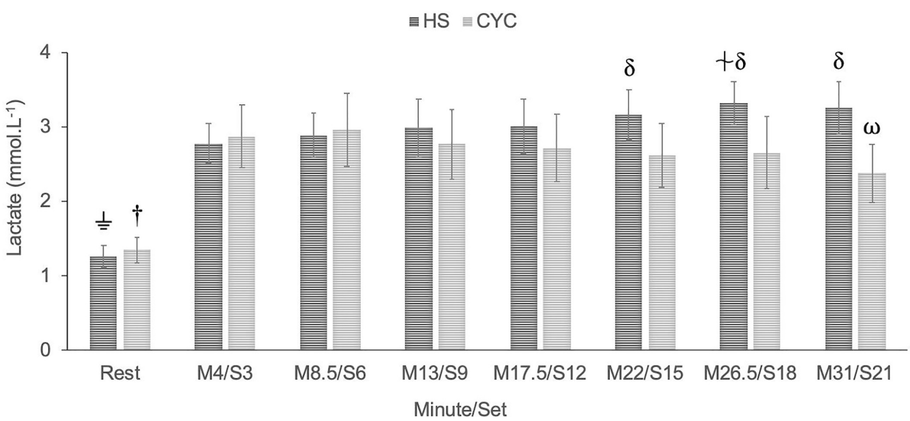

Fig 2. Multiple comparisons between cycle ergometer (CYC) and half-squat (HS) in blood lactate. ⏚ Significantly different from S3, S6, S9, S12, S15, S18, S21 in HS exercise, $p < 0.001$. † Significantly different from M4, M8.5, M13, M17.5, M22, M26.5, M31 in cycle ergometer, $p < 0.01$. δ Significantly different from cycle ergometer in M22/S15, M26.5/S18, M31/S21, $p < 0.05$. ω Significantly different from M4 in cycle ergometer, $p = 0.028$. ∔ Significantly different from S3 and S6 in HS exercise, $p < 0.05$.

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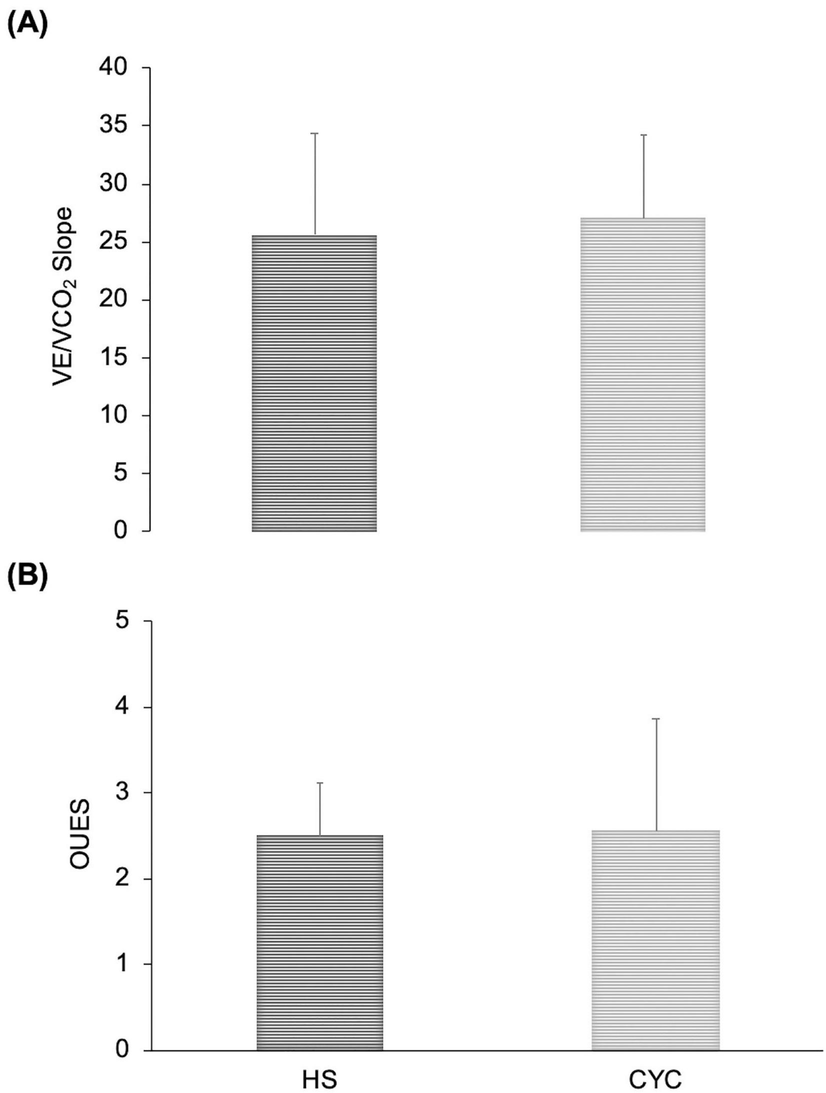

Fig 3. Differences between cycle ergometer (CYC) and half-squat (HS) in the VE/VCO_2 slope and OUES. No significant differences between both exercise modalities.

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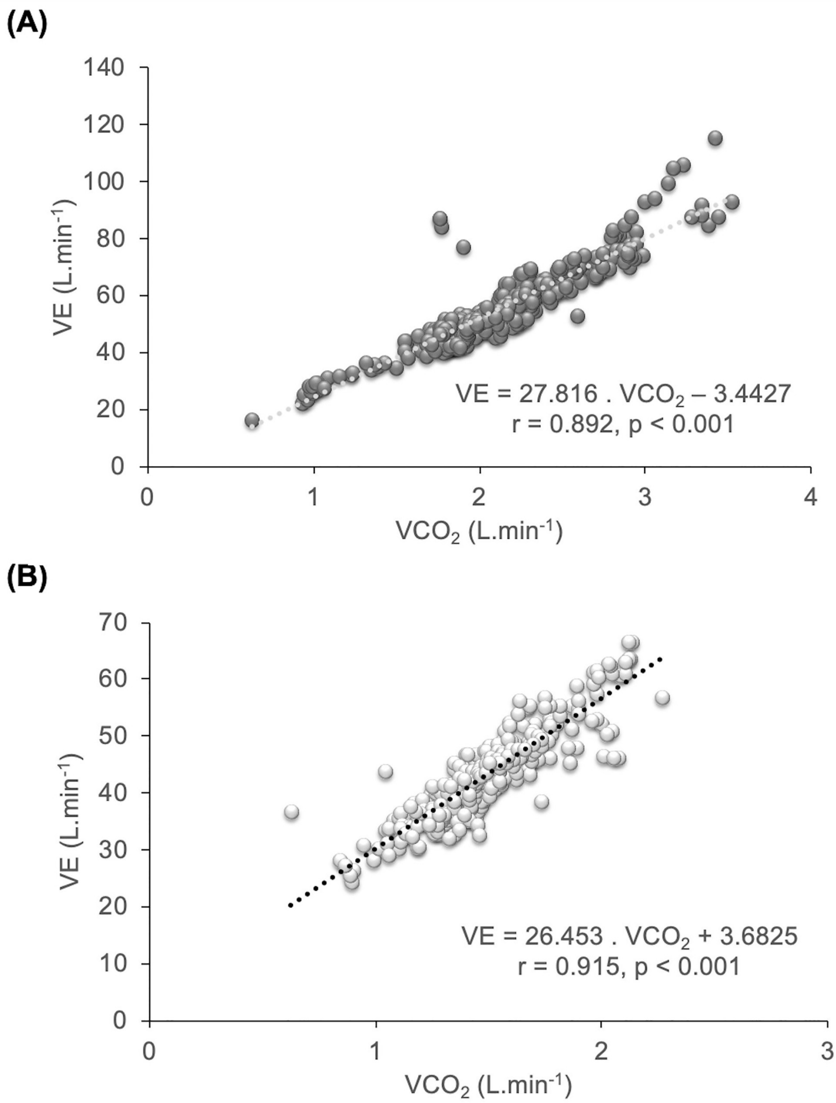

Fig 4. Linear relationship between ventilation (VE) and carbon dioxide (VE/VCO2 slope): (A) Cycle ergometer (CYC). (B) Half-squat (HS).

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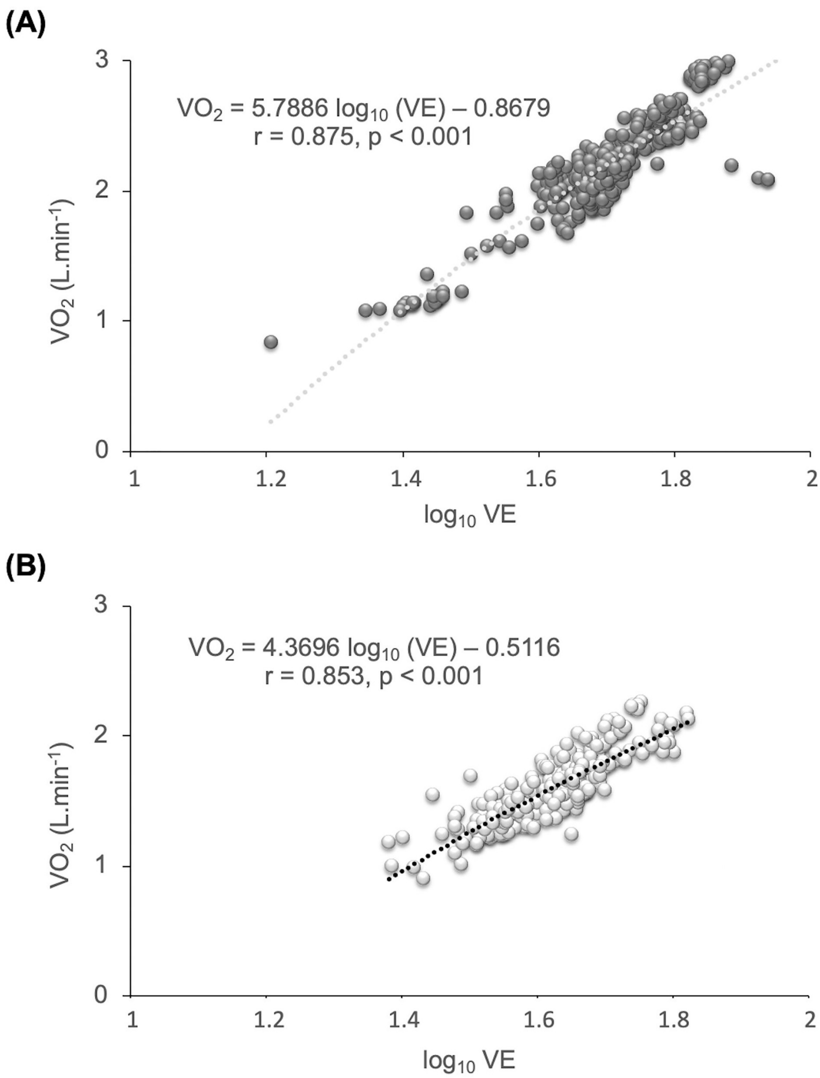

Fig 5. Relationship between oxygen uptake (VO_2) and log_{10} VE (OUES): (A) Cycle ergometer (CYC). (B) Half-squat (HS).

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intensities (LT and anaerobic thresholds) reflect a similar metabolic moment, beyond which lactate concentrations begin to increase. Our data from both exercise modes in healthy young adults verify that this protocol could be another option to evaluate the slope of VE/VCO_2 and OUES in a mostly aerobic metabolism, controlling the acidosis of the body, without having to reach the high intensities and avoiding a higher cardiorespiratory stress that could become problematic in some pathologies. Probably, during a constant-load test at moderate intensity (LT) the relationship between VE and both VCO_2 and VO_2 is normally stable and uniform before the onset of ventilatory compensation for the exercise-induced lactic acidosis [10], justifying, at least in part, the similarities detected in VE/VCO_2 slope and OUES between both exercise modalities at the same metabolic state.

A surprising aspect of this study was the almost identical values in the ventilatory efficiency observed in the HS and cycle ergometer tests. Studies comparing the VE/VCO_2 slope and the OUES in different types of exercises are rare; therefore, there is a significant lack of information about which exercise modality could induce a higher ventilatory efficiency. Our findings show that two types of exercise with different cardioventilatory responses induce the same ventilatory efficiency at similar metabolic intensity. During incremental exercise tests [23], no significant changes were found between treadmill and cycle ergometer trials, although both exercise modalities showed a lower VE/VCO_2 slope (higher efficiency) compared to a robotics-assisted tilt table. A study compared OUES in 17 healthy subjects in two exercise modalities, observing higher values in the treadmill test compared to the cycle ergometer [24]. Although further evidence is needed, ventilatory efficiency could be dependent on the type of exercise, test protocol, and mode of assessing ventilatory efficiency (OUES vs VE/VCO_2 slope).

It was expected that subjects with a lower VE/VCO_2 slope (greater efficiency) throughout each of the tests would increase their OUES. The lack of significant correlation between the OUES and the slope of the VE/VCO_2 in the two exercise modalities analyzed indicates that those subjects who showed greater ventilatory efficiency in the HS did not achieve greater ventilatory efficiency in the cycle ergometer. The OUES has been accepted as a valid submaximal measure of the function and prognosis of disease [39], and the slope of VE/VCO_2 is a reliable assessment in healthy adults [40] and in those with pathologies [41]. However, their usefulness in healthy and athletically trained people is dubious. It is not yet clear which factors contribute to modify ventilatory efficiency during exercise, but the established postulates through this discussion may be more relevant in the clinical field than in fitness and sports performance because it seems that the VE/VCO_2 slope did not change in elite cyclists after 16 weeks of training [11] and, regardless of gender, in children [42] and healthy adults [10] engaging in exercise. Training did not improve the OUES in healthy subjects [43] and could have a limited effect in athletes [11].

As a practical application, these findings could be an interesting alternative for the processes of physical rehabilitation and recovery from diseases associated with a loss of strength and muscle mass. For example, patients with heart failure are characterized by a significant loss of muscle mass, and these same physiological mechanisms are closely related to dyspnea and ventilatory fatigue [44]. Therefore, ventilatory efficiency is related to the severity of heart failure with reduced ejection fraction [45, 46] and, as a corollary, poor ventilatory efficiency is related to increased morbidity and mortality. In addition, it is common to diagnose strength and muscle loss (sarcopenia) in older adults. Sarcopenia is a prevalent syndrome associated with premature mortality in elderly [47]. Resistance exercises at LT intensity could increase local muscular endurance avoiding the losses of strength and muscular mass and, in addition, with the same ventilatory efficiency that could produce the cycle ergometer exercise. Unfortunately, our arguments cannot be consolidated with previous studies in different pathologies, as data clarifying the effect of the resistance exercises to LT intensity in patients with heart failure or sarcopenia are not available; therefore, these observations remain purely intuitive and speculative. It is clear that the combination of both resistance and endurance training has improved exercise capacity and diastolic function in patients with heart failure with reduced ejection fraction [48]. Accordingly, the combination of resistance exercises and endurance exercises could be an adequate methodology to increase cardiorespiratory response (endurance exercises) on the one hand and strength and muscular resistance (resistance exercises) on the other hand.

There are some limitations in this study with regard to the HS exercise protocol, which should be considered. The experimental procedures established in both incremental tests prompt controversial debate with regards to the location of the LT. Consequently, the relative intensity or external load prescribed in each exercise could have been different during both constant-load tests. In this case, an important bias would occur when comparing ventilatory efficiency, cardiorespiratory and metabolic responses between both exercises. However, the results reported by our research group in a recent study [49] revealed that the detection of the LT in both exercises using this same methodology could occur at a similar metabolic instant and relative intensity according to the criteria defined by Binder et al. [50]. In both incremental tests, an equivalent load intensity was produced at the LT, however, cardiorespiratory response was higher in cycle ergometer than in HS exercise during constant-load tests. It is habitual to observe an unequal cardioventilatory response when several exercise modes are compared at the same relative intensity or external load [51]. An identical trend was found in other studies that compared blood lactate, RER and cardiorespiratory responses in various exercises at lower and moderate intensities [38, 52]. Probably, cardiorespiratory responses are exercise mode-dependent at the same metabolic intensity and, therefore, these differences seem larger and more important to considerer at lighter and moderate intensities [38].

We cannot fail to mention that the recovery time established between each series is a key factor in maintaining low and stable levels of blood lactate in a primarily aerobic metabolism. It is assumed that this rest period would mainly affect the mechanisms of cardioventilatory recovery. However, our research group has observed in preliminary trials (unpublished data) that the combination of resistance exercises (in the form of circuit training), without rest between exercises, could keep blood lactate concentrations low and stable. The results stated in this study have important implications for our understanding of the load intensity and the recovery time that regulate ventilatory efficiency in a predominantly aerobic metabolism in HS exercise. Probably, a discontinuous constant-load HS test might induce a similar metabolic intensity and ventilatory efficiency as occurred during continuous constant-load cycle ergometer test. Further studies are needed to determine if the hypothetical increase in VO_2 and ventilation associated with a continuous protocol without recovery time between series would increase ventilatory efficiency in the resistance exercises to LT intensity.

Conclusions

Our findings showed that:

1. Cardioventilatory response was lower in HS exercise than in cycle ergometer during a constant-load test at LT intensity.
2. Ventilatory efficiency was equally efficient in the HS resistance exercise and in cycle ergometer exercise in a predominantly aerobic metabolism, which could have a significant impact in healthy people.

3. There was no correlation between the OUES and the slope of the VE/VCO_2 in the two exercise modalities analyzed. Those subjects who showed greater ventilatory efficiency in the HS did not achieve higher ventilatory efficiency in the cycle ergometer.
4. Performing a constant-load HS protocol at LT intensity does not generate significant cardiorespiratory stress, while ventilatory efficiency is maintained and muscle strength and local muscular endurance, as well as gross mechanical efficiency, may improve according to previous findings of our research group.

Further research is needed to analyze ventilatory efficiency for better understanding of ventilatory mechanisms that conditioning resistance exercises performance in a predominantly aerobic metabolism.

Supporting information

S1 File. Statistical analysis performed with the data obtained during constant-load test.
(DOC)

S1 Fig. Results for the preparation of the figures.
(XLSX)

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D. *Marcos Faundez Zanuy* en calidad de Presidente de la Comisión de Investigación de la Fundación del TecnoCampus-Mataró, centros adscritos a la Universidad Pompeu Fabra.

CERTIFICO:

Que, *el Comité de ética e investigación de dicha Fundación, en la sesión celebrada en el día de hoy ha evaluado el proyecto de investigación titulado*:

"Análisis de las respuestas cardiorrespiratorias, mecánicas, hormonales, de estrés oxidativo y electromiográficas en los ejercicios con resistencias", cuyo investigador principal es el profesor Manuel V. Garnacho Castaño.

El proyecto de investigación se enmarca dentro de las líneas de investigación del centro y que cumple con los requisitos metodológicos necesarios, es viable en todos los términos y sigue las directrices establecidas en los principios de la Declaración de Helsinki para la investigación con seres humanos.

Y para que así conste, a petición del interesado, expido el presente certificado en Mataró a 23 de Marzo del 2018

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