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ANÁLISIS BIOMECÁNICO Y FISIOLÓGICO DE LA INFLUENCIA DEL CALZADO DEPORTIVO EN EL RENDIMIENTO DEL CORREDOR

Tesis Doctoral Internacional presentada por:

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*Para la persona que ha llevado a nuestra familia a la máxima plenitud,
va por ti papá.*

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Publicaciones

La presente Tesis Doctoral está compuesta por las siguientes publicaciones científicas:

I. **Ruiz-Alias, S. A.**, Molina-Molina, A., Soto-Hermoso, V. M., & Garcia-Pinillos, F. (2023). A systematic review of the effect of running shoes on running economy, performance and biomechanics: analysis by brand and model. *Sports Biomechanics*, 22(3), 388-409.

II. **Ruiz-Alias, S. A.**, Jaén-Carrillo, D., Roche-Seruendo, L. E., Pérez-Castilla, A., Soto-Hermoso, V. M., & García-Pinillos, F. (2023). A review of the potential effects of the world athletics stack height regulation on the footwear function and running performance. *Applied Sciences*, 13(21), 11721.

III. **Ruiz-Alias, S. A.**, Pérez-Castilla, A., Soto-Hermoso, V. M., & García-Pinillos, F. (2023). influence of the world athletics stack height regulation on track running performance. *The Journal of Strength & Conditioning Research*, 37(11), 2260-2266.

IV. **Ruiz-Alias, S. A.**, Pérez-Castilla, A., Soto-Hermoso, V. M., & García-Pinillos, F. (2023). The effect of using marathon shoes or track spikes on neuromuscular fatigue caused by a long-distance track training session. *International Journal of Sports Medicine*, 44(13), 976-982.

V. **Ruiz-Alias, S. A.**, Pérez-Castilla, A., Soto-Hermoso, V. M., & García-Pinillos, F. (2024). Influence of the carbon fiber plate curvature on the running energetic cost and 3000-m performance. *Sports Engineering*, 27, 21.

Resumen

De 2017 a 2019, la biomecánica y fisiología del corredor se encuentran en su máximo esplendor siendo la barrera de las 2 horas en maratón el eje conductor de su desarrollo. Tras su éxito, el calzado deportivo se vuelve el foco principal de todo corredor dada la evidente mejora de sus prestaciones reflejadas en el cronómetro. A consecuencia de ello, la World Athletics emana una regulación del calzado, algo no visto hasta la fecha, con la finalidad de limitar esta evolución del rendimiento exponencial. Surgen por entonces calzados deportivos legales e ilegales en función del contexto de la competición. Entre los elementos diferenciadores de esta novedosa línea de calzado deportivo de tecnológica avanzada, una placa de carbono en el eje longitudinal centra toda la atención como el elemento diferenciador.

Dada la revolución experimentada, con la finalidad de aportar un conocimiento clarificador y evidencia científica a las necesidades presentes de la temática, el objetivo de esta Tesis Doctoral ha sido analizar el efecto de esta novedosa línea de calzado deportivo de tecnología avanzada en el rendimiento del corredor desde la perspectiva biomecánica y fisiológica. Para ello, se procedió a realizar una revisión sistemática y narrativa de la literatura para exponer los antecedentes de la temática y determinar las nuevas vías de estudio (Artículo I y II). De estos, surgen tres estudios experimentales donde se determinan el efecto de modelos de calzado legales e ilegales en el rendimiento del corredor en un contexto competitivo en pista (Artículo III), así como en la biomecánica y fatiga neuromuscular (Artículo IV), y finalmente, el efecto de la geometría de la placa de carbono en el rendimiento del corredor a intensidades submáximas, máximas y en estado de fatiga (Artículo V).

Abstract

From 2017 to 2019, the biomechanics and physiology of running reached its peak being the 2 hours marathon barrier the underlying cause of its development. After its success, a new running shoe trend captured the attention of all kinds of runners given the significant improvements seen in the stopwatch. Consequently, the World Athletics implemented an unprecedented running shoe regulation intending to limit this exponential trend of improvements. Then, the first legal and illegal running shoes appear according to the competition context. Of the different elements of the so-called advanced footwear technology, a carbon fiber plate placed through the longitudinal axis was deemed as the game-changing of this improvement in running performance.

Given the revolution experienced, with the aim of providing some new clarifying knowledge and scientific evidence to the existing needs of this topic, this Doctoral Thesis has aimed to analyze the effect of this new advanced footwear technology on running performance from a biomechanical and physiological perspective. To this end, a systematic and narrative review was performed to expose the topic's background and determine new avenues to study (Articles I and II). From these, three experimental studies emerged where the effect of legal and illegal running shoes on running performance was determined in a track competition context (Article III), as well on running biomechanics and neuromuscular fatigue (IV), and finally, the effect of the carbon fiber plate geometry on running performance at submaximal, maximal intensities and in a fatigued state (Article V).

The main results of this Thesis suggest that: a) The use of illegal advanced footwear technology leads to a significant performance improvement compared to the legal model. b) The performance improvement is associated with a reduction of ground

contact times as well as with an increase in step length, particularly, at the end of the trial.

c) Likewise, athletes display lower neuromuscular fatigue for the same mechanical work performed. d) Finally, the geometry of the differentiating element, the carbon fiber plate, is determinant in the running performance at both submaximal and maximal intensities. Specifically, when using a flat geometry, athletes display an improvement in the running economy and performance in 3000-m. However, in a fatigued state, athletes display a similar running economy, making the plate geometry in this context irrelevant.

Abreviaturas

- MIME: Máxima intensidad metabólicamente estable
- EC: Economía de carrera
- VO2max: Consumo de oxígeno máximo
- MTP: Articulación metatarsofalángica

Introducción

El origen: La barrera de las 2 horas en maratón

La leyenda griega de Filípides dio inicio a uno de los mayores retos que todo corredor se plantea a lo largo de su etapa deportiva, correr una distancia de 42195 m. Sin embargo, en el contexto en el que se desarrolla la sociedad actual, dicho reto se ha convertido en una hazaña ordinaria. Miles de personas comienzan un lunes bajo el título de maratoniano/a, lo que nos plantea la necesidad de reformular la esencia del “reto” de la maratón. Desde el punto de vista metabólico, el ser humano está creado para completar grandes distancias, pero no así para hacerlo a una alta intensidad (1), aunque dicha capacidad ha ido evolucionando a lo largo de los años. Desde 1960, cada década ha supuesto una mejora de 1 a 5 minutos en los mejores registros de maratón (2). Extrapolando esta tendencia, la barrera de las 2 horas en maratón se preveía para el año 2035. Sin embargo, 2019 supuso el fin del proyecto generado por dos grandes marcas deportivas que apostaron por acelerar la evolución del rendimiento humano, estableciendo el 12 de Octubre de 2019 un registro de 1:59:40 (i.e., 21.1 km/h; 2:50 min/km).

Para entender este punto de inflexión en el rendimiento es necesario detenernos en analizar cada uno de los elementos que compusieron el proyecto denominado “Breaking2”. Publicaciones posteriores revelaron que la élite del maratón fue reclutada para conocer sus características fisiológicas y seleccionar así las más privilegiadas (3). Específicamente, la determinación de dos variables reflejó si el reto era fisiológicamente viable. Por un lado, la denominada máxima intensidad metabólicamente estable (MIME) (4) debía de posicionarse próximos a los 21 km/h, la intensidad necesaria para alcanzar las 2:00:00 en maratón. De los 16 atletas de élite reclutados, solo 7 cumplieron dicha

condición. Sin embargo, presentar una estabilidad metabólica a 21 km/h no les aseguraba llegar a meta, era necesario considerar junto a esta la denominada economía de carrera (EC) (i.e., el gasto energético ante un determinado trabajo externo). Para el promedio de este subgrupo (i.e., ~ 191 ml/kg/km), la mejor estimación del rendimiento apuntaba a un posible registro de 2:00:01. Hoy en día sabemos que Eliud Kipchoge era el privilegiado de dichas asombrosas capacidades fisiológicas, pero ¿por qué no había corrido más rápido de las 2:02:37 que ostentaba por entonces?

De estas dos variables cruciales en el rendimiento de la larga distancia (i.e., MIMS, EC), la EC es susceptible de modificación mediante la alteración de ciertos elementos externos que mejoren el balance entre el gasto energético y el trabajo mecánico producido, además de los factores que la determinan por parte del propio atleta. En el pistoletazo de salida de la mañana del 12 de Octubre se descubrieron los detalles que permitieron que la EC resultante de Kipchoge fuese ese día excepcional (**Figura 1**). Entre las más destacables, Eliud contó con un conjunto de liebres rotatorias dispuestas en una formación de “V” con la finalidad de minimizar el impacto del viento. Junto a esto, el circuito se seleccionó minuciosamente teniendo en cuenta aspectos como el número de curvas y las pendientes que le penalizaron en su anterior intento de récord en el circuito de Monza (i.e., 2:00:25) (5). Sin embargo, el diseño del calzado que por primera vez utilizaba en competición captó la atención de todos los espectadores, y especialmente, cuando el cronómetro se pausó.



Figura 1. Factores externos que se consideraron para bajar de las 2:00:00 en maratón con la finalidad de mejorar la economía de carrera.

Las primeras investigaciones que comenzaron a desglosar el efecto de estos modelos revolucionarios de competición indicaban que la EC mejoraba aproximadamente un 4% respecto a los modelos utilizados en los anteriores récords de maratón (6). Para entender su repercusión sobre el cronómetro, establezcamos el siguiente supuesto. Un atleta elite de maratón tiene un consumo de oxígeno de 67 ml/kg/min a 21 km/h, una MIMS asumible para un atleta de elite con un consumo de oxígeno máximo (VO_{2max}) cercanos a los 80 ml/kg/min (85% VO_{2max}) (3). Junto con un valor de EC de 200 ml/kg/min, el cronómetro se detendría aproximadamente en 2:04:08. Considerando la mejora del 4% si el atleta opta por calzarse esa mañana este revolucionario modelo, se estima que el cronómetro se pararía en 1:59:45 (i.e., $60 \cdot 67 / 192 = 21.2$ km/h).

Dopaje tecnológico: ¿Mito o realidad?

La mejor marca mundial de la historia en maratón nos hace reflexionar acerca de las variables que conforman la ecuación del rendimiento y el peso que adquiere cada una de estas. Podríamos afirmar que el atleta no corre solo, reconociendo así la labor del equipo de trabajo que le acompaña en el proceso (i.e., entrenador, fisioterapeuta, nutricionista, fisiólogo, biomecánico). En este aspecto, Macnamara et al (7) da cierta evidencia a esta afirmación al observar que la práctica deliberada solamente explica un 1% de la varianza del rendimiento entre deportistas de élite. Es decir, si el atleta de élite entrena como un atleta de élite, existen otros elementos que marcarán la diferencia en el rendimiento.

Junto al equipo de trabajo, el desarrollo tecnológico del siglo XXI es el tercer elemento innegable. Su repercusión en el rendimiento sabemos que es significativo (6), pero no estratosférico. En este aspecto, se llegó a especular que esta nueva tipología de calzado ejercía de muelle, facilitando así el desplazamiento por méritos mecánicos. Aunque es cierto que la Ley de Hooke se utiliza para describir el comportamiento y las prestaciones del material de la media suela del calzado deportivo, las leyes básicas de la mecánica desmienten dicha especulación. Concretamente, la segunda ley de Newton establece que toda acción genera una reacción de igual magnitud, pero en sentido opuesto. En este aspecto, la fuerza de reacción de la media suela viene determinada por su deformación y la constante de resistencia. Sin embargo, durante esta, parte de la energía de acción se disipa en forma de calor. Por tanto, cabe destacar que la reacción mecánica no puede superar la acción humana. En este sentido, Hoogkamer et al. (6) reportaron que el nuevo material utilizado en esta gama de calzado de tecnología avanzada duplica la deformación observada en los anteriores modelos de maratón y consigue restituir un mayor porcentaje de la acción inicial (i.e., resiliencia), siendo este uno de los motivos de

la mejora de la EC. De la misma forma, dicho efecto muelle se le atribuyó a la novedosa placa de carbono, un aspecto que la literatura desmiente (11) y cuya función, que desglosaremos en el siguiente punto, difiere a la propuesta.

Este no resulta ser el primer caso de discusión de dopaje tecnológico en el atletismo. Las prótesis del velocista australiano Oscar Pistorius fueron también objeto de debate al considerar que mejoraba la función de la pierna humana (11). Recordando que la acción determina la reacción, la igualdad entre atletas en este caso limita gran parte de la discusión. ¿Y qué ocurre con los récords mundiales de generaciones anteriores? Esta parece ser la gran cuestión que llevó a la World Athletics en 2020 a establecer un reglamento en el calzado deportivo (12), algo no visto hasta la fecha. La justificación al respecto: Es necesario asegurar que el rendimiento, incluyendo los récords, sean conseguidos mediante la primacía del esfuerzo humano sobre la tecnología en el calzado.

¿El fin de la revolución? La regulación de la Word Athletics

En 2020, la World Athletics establece que la media suela no puede superar un determinado grosor (**Figura 2**) en función del evento de competición (**Tabla 1**).



Figura 2. Ilustración de medición del grosor de la media suela.

Tabla 1. Máximo grosor de la media suela permitido para cada evento de carrera.

Event	2020–2022	2022–2024	2024
<800 m	20 mm	20 mm	20 mm
≥800 m	25 mm	25 mm	20 mm
Road	40 mm	40 mm	40 mm
Cross	25 mm spike shoe or	20 mm spike shoe or	20 mm spike shoe or
Country	non-spike shoe	40 mm non-spike shoe	40 mm non-spike shoe

El efecto de su llegada se resume muy bien en la situación vivida en la maratón de Vienna de 2021(12). Derera Hurisa cruza la línea de meta como ganador en 2:09:22, seguido por Leonard Langat con un registro de 2:09:25, a 3 segundos de diferencia. Tras finalizar la prueba, a Deresa se le comunica su descalificación por haber utilizado el modelo “Adidas Adizero Prime X”, con 50 mm de grosor, ilegal para los eventos de ruta (≤ 40 mm). Langat, sin embargo, calzó las “Adidas Adizero Adios Pro 2”, dentro del límite permitido, ganando “legalmente” la prueba. Hoy en día sabemos que dicha descalificación fue injusta en base a los resultados aportados por Barrons et al. (14). Estos autores evaluaron la EC de 21 corredores recreacionales al hacer uso de 4 prototipos de Adidas con distintos tamaños de la media suela (i.e., 35, 40, 45 y 50 mm), manteniendo de forma similar el resto de características (i.e., geometría, peso), obteniendo una EC similar entre condiciones.

La regulación fue también objeto de discusión en el contexto científico. Por un lado, Burn y Tam (15) inician este debate afirmando que limitar el tamaño de la media suela supondrá una medida integradora que limite todos los elementos del calzado que contribuyen a la mejora de la EC. Además, añaden que al restringir el espacio disponible se evitarán futuras innovaciones para así salvaguardar la integridad del atletismo. En respuesta a estas afirmaciones, Frederick (16), editor jefe de la revista Footwear Science se contrapone a esta propuesta ya que el diseño de los modelos actuales no son uniformes

y esto no permite medir con exactitud el grosor de la media suela. En la misma línea, Hoogkamer (17) argumenta que aumentar el grosor de la media suela no implica una mejora de la EC dado el incremento de peso y el aumento de la inestabilidad en el eje mediolateral. Además, Hoogkamer (17) aporta un argumento interesante respecto al comportamiento de la media suela. Este establece que la resiliencia no se ve comprometida por dicha limitación ya que la deformación de estos últimos materiales no supera los 12 mm, muy lejano del máximo grosor permitido, necesitando solo unos mm más para evitar el estancamiento del material y mantener así sus máximas prestaciones. Finalmente, Nigg et al. (18) contribuyen en este debate resaltando los elementos del calzado que podían contribuir a la EC, junto con un análisis de la magnitud de sus contribuciones. En este aspecto, Nigg et al. (18) resaltan que la gran mejora del rendimiento en carrera proviene de incrementar la rigidez longitudinal del calzado a través de la placa de carbono junto con un aumento del rocker de la media suela en el antepié (i.e., la curvatura hacia arriba de la suela en el antepié) generando así el denominado efecto balancín (19) que detallaremos en profundidad en el siguiente punto.

A pesar de su implementación, la regulación de la World Athletics no limitó que los récords mundiales continuasen descendiendo (20). Todo esto nos motivó a realizar un análisis sistemático de la literatura con el que recopilar la evidencia existente entorno al efecto del calzado en tres pilares fundamentales: La fisiología, biomecánica y el rendimiento del corredor (**Artículo I**), para así fundamentar el origen y la magnitud de dichos cambios. Junto a esto, decidimos realizar un segundo trabajo de revisión con el que discutir, en base a la evidencia existente, qué efectos podría ocasionar la reducción del grosor de la media suela en la función de cada elemento del calzado que contribuía a mejorar la EC, así como su interacción con el corredor (**Artículo II**). Dicho marco teórico y huecos en la literatura se expone en el siguiente punto.

Decodificando el calzado de tecnología avanzada

Si consideramos el calzado de carrera como un elemento facilitador del rendimiento, la literatura nos categoriza 3 vías de mejora basadas en la minimización y almacén de la energía mecánica:

El peso del calzado

El peso del calzado de carrera ha sido uno de los elementos más estudiados. Desde 1984 a 2016, los tres principales estudios que abordan el efecto de este elemento en el rendimiento arrojan una penalización consistente del 1% en la EC por cada 100 gramos de peso (26-28). El interés por este elemento recae en la tendencia progresiva a aumentar el tamaño de la media suela, dando lugar a la categorización del calzado de carrera por minimalista y maximalista, observándose en este último modelos con hasta 50 mm de grosor. Sobre este aspecto, Barrons et al. (29) reporta un aumento de 50 gramos de peso por cada incremento de 15 mm en el grosor de la media suela para un mismo calzado manteniendo el resto de las características. Por tanto, esto nos lleva a pensar si la regulación actual, reduciendo el grosor de la media suela permitido (i.e., hasta los 20 mm en los eventos de pista), resulta ser acorde a su intencionalidad de limitar el rendimiento. En este contexto, el uso de un calzado legal podría suponer una mejora del rendimiento dada su ligereza respecto a un calzado ilegal donde el “exceso” de media suela podría estar penalizando al atleta al aumentar la demanda mecánica de la fase de oscilación de la carrera. Este trabajo mecánico denominado trabajo interno se acrecenta en particular conforme aumenta la velocidad en carrera (30), lo que nos motivó a analizar el efecto de dos calzados de competición categorizados por maximalista (ilegal) y minimalista (legal) en el rendimiento de corredores de alto nivel en pruebas de medio fondo en pista (**Artículo III**), considerando también su interacción con la media suela.

Las propiedades de la media suela

La media suela puede contribuir al rendimiento de corredor mediante el comportamiento del material que la conforma, deformándose para almacenar energía potencial elástica, y restituyéndola en forma de energía cinética (9). Sobre este aspecto, Hoogkamer et al. (6) aporta una clara evolución de los materiales utilizados en el calzado de competición. A través de un test mecánico recreando las fuerzas experimentadas por un corredor de 68 kg a 18 km/h (i.e., 2000 N en 185 ms), la media suela utilizada en el calzado con el que se batió el actual récord de maratón presenta una deformación de 12 mm, dando lugar a un retorno de energía de un 87%, siendo ambas funciones significativamente superiores a los materiales utilizados en el calzado de los anteriores récords de maratón (i.e., 6 mm y 65%, 6 mm y 76%). Aislado su efecto respecto al resto de elementos, Worobets et al. (31) reporta una diferencia del 1% en la EC para un 10% de diferencia en el retorno de energía del material, por lo que su contribución parece ser significativa. En este aspecto, Nigg et al. (18) matiza que la resiliencia del material solo es transferida al rendimiento del atleta si la fase de almacén y restitución se sincronizan con las fases del tiempo de contacto. Asimismo, Hoogkamer et al. (17) discute otro elemento a considerar planteando la siguiente cuestión ¿Es necesario un determinado grosor para alcanzar la máxima deformación del material y por consiguiente su máxima energía de retorno? Unificando ambas consideraciones (i.e., “timing” y grosor de la media suela), los resultados de Barrons et al. (29) clarifica este planteamiento al observar que una misma media suela con distintos grosores, mantiene su resiliencia mediante la modificación de la rigidez del material. Por tanto, cabe de esperar que la energía de retorno de un mismo material se refleje en el rendimiento del atleta en función del grosor de la media suela y el tiempo de contacto del atleta (**Artículos III y IV**).

La placa de carbono

A pesar de su reciente repercusión, la placa de carbono no resulta ser un elemento novedoso en la literatura científica. Su origen se establece en 1996 mediante el conjunto de artículos que conforman la tesis doctoral de Darren Stefanyshyn (32), con la que se establece los principios de este elemento. La motivación por incluir una placa de carbono en el eje longitudinal del calzado surge del análisis del trabajo mecánico positivo y negativo de las distintas articulaciones implicadas en la carrera. Específicamente, el interés se centra en la denominada articulación metatarsofalángica (MTP) del Hallux, caracterizada por un realizar exclusivamente un trabajo negativo durante su dorsiflexión en la fase de propulsión (i.e., trabajo que no contribuye al desplazamiento). Por tanto, si limitamos dicha dorsiflexión mediante el incremento de la rigidez longitudinal del calzado, la eliminación del coste energético asociado dará una mejora en la EC. Estudios independientes de Darren confirman la inhibición de la dorsiflexión de la MTP, resultando en una mejora del 1% en la EC (33, 34).

Sin embargo, al reducir la dorsiflexión, Darren et al. (34) observan un aumento del torque del tobillo a consecuencia de un aumento del brazo de palanca (i.e., distancia del punto de aplicación de la fuerza de reacción respecto al eje articular del tobillo), lo que podría explicar la dependencia de las mejoras en EC al peso corporal de los atletas evaluados. Este efecto secundario de incrementar la rigidez longitudinal del calzado parecer ocasionar dos vías de respuesta en el atleta: 1) se produce una reducción de la velocidad angular de la flexión plantar lo que permite al atleta ejercer un menor pico de fuerza, y distribuir el trabajo mecánico durante más tiempo (i.e., mejora de la EC), 2) se mantiene la velocidad angular de la flexión plantar, ejerciendo una mayor fuerza pico para solventar el aumento del torque en un mismo tiempo (i.e., deterioro de la EC) (35, 36). Sobre este aspecto, el tiempo disponible para ejercer un determinado trabajo mecánico

parece estar relacionado con el reclutamiento de un mayor o menor número de unidades motoras (i.e., principio de Henneman), siendo por tanto un elemento determinante en el coste energético (37).

Dada esta posible dualidad, el calzado continúa evolucionando y se opta por aportar una geometría curva a la placa de carbono con la finalidad de generar el denominado “efecto balancín” (19). Por una parte, la rigidez de la placa de carbono posiciona el Hallux en dorsiflexión inhibiendo de esta forma su desplazamiento en la fase de propulsión. Por otra parte, el punto de aplicación de fuerza mantiene su posición original en la fase de propulsión, inalterando por tanto el brazo de palanca de la articulación del tobillo. Asimismo, la geometría curva ocasiona una palanca de primer género, transfiriendo la fuerza de acción ejercida en el antepié en una fuerza de reacción en el retropié durante la fase de propulsión, facilitando así la flexión plantar. Sobre este mecanismo, Rodrigo-Carranza et al. (38) observan un aumento de la EC del 4% en atletas recreacionales, y del 2% en atletas de alto nivel al hacer uso de una placa de carbono curva respecto a una condición control sin placa.

Sin embargo, hasta la fecha, ningún estudio ha abordado la comparativa del efecto de una placa de carbono plana y curva en la EC, lo que clarificaría en gran medida su efectividad (**Artículo V**). En este aspecto cabe destacar otro hueco en la literatura existente en torno al efecto del calzado en la EC. Las normativas de medición establecen que la EC solo se debe registrar a intensidades por debajo del primer umbral ventilatorio (39). Dicha intensidad solo es representativa de corredores recreacionales en maratón (40), por lo que la biomecánica de carrera y las propiedades mecánicas del calzado no se analizan en el contexto real de competición de la gran parte de pruebas y atletas. Asimismo, las tandas de medición por debajo del primer umbral ventilatorio, espaciadas por amplios tiempos de recuperación (en la investigación del calzado, por el simple hecho

de cambiar de un modelo a otro) evitan el desarrollo de la fatiga, un elemento crucial en la biomecánica del corredor (i.e., el trabajo mecánico ejercido por tobillo, rodilla y cadera evolucionan a lo largo de un esfuerzo a la extenuación) (41,42). Por ello, en el **artículo V** planteamos la necesidad de innovar en las metodologías de análisis realizadas hasta la fecha, realizando un análisis de la EC sin fatiga, con fatiga, así como en el rendimiento de forma directa.

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Objetivos

General

Analizar el efecto de esta novedosa línea de calzado deportivo de tecnología avanzada en el rendimiento del corredor desde la perspectiva biomecánica y fisiológica.

Específicos

- Realizar una búsqueda sistemática de la literatura para recopilar la evidencia existente en el efecto del calzado en la economía, biomecánica y rendimiento del corredor, con el fin de detectar futuras vías de estudio (Artículo I).
- Analizar la literatura existente en torno al impacto de la regulación de la World Athletics en las funciones del calzado de tecnología avanzada, y en el rendimiento del corredor para así clarificar el estado actual del contexto de competición (Artículo II).
- Determinar el efecto del calzado considerado por la World Athletics por legal e ilegal para su uso en pista sobre el rendimiento y la biomecánica del corredor (Artículo III), así como en la fatiga neuromuscular (Artículo IV).
- Analizar el impacto de la geometría de la placa de carbono sobre el rendimiento y la economía de carrera del corredor en distintos grados de fatiga (Artículo V).

Material y Métodos

Los materiales y métodos empleados en los artículos que conforman la presente Tesis se disponen a modo de resumen en la Tabla 1.

Tabla 2. Resumen de la metodología empleada en la presente Tesis.

Artículo	Diseño	Participantes	Protocolo	Variables independientes	Variables dependientes
I. A systematic review of the effect of running shoes on running economy, performance and biomechanics: analysis by brand and model.	Revisión sistemática	<i>n</i> = 36 artículos con atletas entrenados	Búsqueda en bases de datos: Web of Science, SPORTDiscuss, PubMed y Scopus desde 2015 a 2022 Términos de búsqueda: (Run*) AND (Shoe* OR Footwear OR Racing Flats OR Spikes) AND (Economy OR Energy Cost OR Metabolic Cost OR Energy Expenditure) AND (Time OR Race OR Speed OR Pace) AND (Efficiency OR Biomech* OR Kinetic OR Kinematic OR Spatiotemporal)	61 modelos de calzado deportivo de diversas categorías: -Calzado minimalista -Calzado maximalista -Calzado de competición	Economía de carrera Rendimiento Parámetros espaciotemporales Fuerzas de reacción del suelo Rigidez articular Tendón de aquiles Presiones plantares Carga tibiofemoral Patrón de contacto inicial Coordinación articular
II. A review of the potential effects of the world athletics stack height regulation on the footwear function and running performance.	Revisión narrativa	<i>n</i> = 16 artículos con atletas de diversos niveles	Búsqueda en bases de datos: Pubmed, Web of Science sin límite de fechas. Términos de búsqueda: (Shoe* OR Footwear OR Racing Flats OR Spikes) AND (Mass OR Midsole OR Longitudinal stiffness) AND (Economy OR Energy Cost OR Time OR Race OR Speed OR Pace).	Peso: Diferentes pesos de calzado Propiedades de la media suela: Diferentes materiales Efecto balancín: Diferentes modelos con y sin placa de carbono	Efecto del tamaño de la media suela en los componentes del calzado asociados al rendimiento: Peso Propiedades de la media suela Efecto balancín

Tabla 2. (cont)

Artículo	Diseño	Participantes	Protocolo	Variables independientes	Variables dependientes
III. Influence of the world athletics stack height regulation on track running performance.	Medidas repetidas contrabalanceadas	$n = 14$ atletas de alto rendimiento	Pruebas de tiempo: 9-min Recuperación: 30-min 3-min	Calzado ilegal: Nike ZoomX Vaporfly Next % 2 Calzado legal: Nike ZoomX Dragonfly	Distancia completada en las pruebas de tiempo de 9 y 3- min Parámetros espaciotemporales
IV. The effect of using marathon shoes or track spikes on neuromuscular fatigue caused by a long-distance track training session.	Medidas repetidas contrabalanceadas	$n = 14$ atletas de alto rendimiento	Salto en contramovimiento (Pre-post): Pruebas de tiempo: 9-min Recuperación: 30-min 3-min	Calzado de ruta: Nike ZoomX Vaporfly Next % 2 Calzado de pista: Nike ZoomX Dragonfly	Pacing Diferencia pre-post salto en contramovimiento
V. Influence of the carbon fiber plate curvature on the running energetic cost and 3000-m performance.	Medidas repetidas contrabalanceadas	$n = 12$ atletas de alto rendimiento	Día 1: Test incremental: + 1km/h cada 3-min Día 2 y 3: Test de economía de carrera + test de 3000m: 2x5' a VT1 + 3000m + 1x5' a VT1	Calzado con placa de carbono plana: Asics Metaspeed Sky Calzado de con placa de carbono curva: Asics Metaspeed Edge	Economía de carrera sin y en fatiga Tiempo en 3000m

Resultados

Tabla 3. Resumen de los resultados obtenidos en cada artículo que compone la presente Tesis.

Artículo	Resultados
I. A systematic review of the effect of running shoes on running economy, performance and biomechanics: analysis by brand and model.	Se incluyeron un total de 36 artículos, resultando en el análisis del efecto de 61 modelos de calzados deportivos en 10 tópicos diferentes (i.e., economía de carrera, rendimiento, parámetros espaciotemporales, fuerzas de reacción del suelo, rigidez articular, tendón de aquiles, presiones plantares, carga tibiofemoral, patrón de contacto inicial, coordinación articular)
II. A review of the potential effects of the world athletics stack height regulation on the footwear function and running performance.	Se incluyeron un total de 16 artículos con los que se analizó el efecto del tamaño de la media suela en los componentes del calzado asociados al rendimiento (i.e., peso, propiedades de la media suela, efecto balancín)
III. Influence of the world athletics stack height regulation on track running performance.	En las pruebas de tiempo, no se observó un efecto principal del calzado en el rendimiento ($F_{(1,13)} = 0.41$, $p = 0.535$). Aunque no se obtuvo una interacción significativa ($F_{(1,13)} = 2.70$, $p = 0.124$) entre los modelos de calzado (legal vs. ilegal) para las distintas pruebas de tiempo (9 vs. 3-min), el modelo ilegal muestra una tendencia a incrementar ligeramente el rendimiento en la prueba de 3-min un 0.97% (-0.04 a 1.98%). Se observó un efecto principal del calzado en 7 de las 9 variables biomecánicas analizadas rendimiento ($F_{(1,13)} = 4.96$, $p = 0.050$). El análisis de regresión lineal múltiple mostró que los cambios en los tiempos de contacto fue el único predictor significativo de los cambios en el rendimiento ($F_{(1,13)} = 11.88$, $p = 0.005$, R^2 ajustada: 0.476).

Tabla 3. (cont)

Artículo	Resultados
IV. The effect of using marathon shoes or track spikes on neuromuscular fatigue caused by a long-distance track training session.	Se observó un interacción significativa entre el calzado de ruta y pista para las medidas pre-post sesión en el salto en contramovimiento $F_{(1,12)} = 6.80$; $P = 0.023$). Tras finalizar la sesión, este se redujo -1.78 cm (-3.02 a -0.53 cm) con el calzado de pista mientras que se mantuvo con el calzado de ruta (0.28 cm [-1.05 a 1.62 cm]). En la última prueba de tiempo de 3-min, el uso del calzado de pista supuso una reducción progresiva de la longitud de zancada (-0.13 m [-0.04 a -0.22] m) y un aumento de los tiempos de contacto (4.4 ms [1.5 a 7.4 ms]). Por el contrario, el calzado de ruta supuso un mantenimiento de ambos parámetros espaciotemporales.
V. Influence of the carbon fiber plate curvature on the running energetic cost and 3000-m performance.	Se observó una reducción del coste energético con el calzado de placa de carbono plana respecto a la curva en un estado sin fatiga ($p = 0.034$; -1.13 % [-1.92 to -0.11] %). Esta mejora en el rendimiento se mantuvo en la prueba de 3000m ($p = 0.017$; -0.42 % [-0.74 to -0.09] %). Sin embargo, en estado de fatiga, el coste energético fue equiparable entre modelos ($P = 0.207$).

**Artículo 1: Revisión sistemática del efecto del calzado
en la economía, rendimiento y biomecánica de carrera**

**A Systematic Review of the Effect of Running Shoes on Running Economy,
Performance and Biomechanics: Analysis by Brand and Model**

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Abstract

This systematic review aims to synthesize the effects of current shoe models in each shoe category and their specific features on running economy, biomechanics, and performance. Electronic databases such as Web of Science, SPORTDiscuss, PubMed, and Scopus were used to identify studies from 2015 to date. Due to the existing lack of consensus to define running shoes, only studies that specified the shoe brand and models used to assess their effect over runners with a certain level of fitness and training routine were included. The quality assessment of cross-sectional and intervention studies was conducted by three independent raters using a modified version of the Quality Index and the PEDro scale, respectively. A total of 36 articles were finally included, involving the analysis of 61 different shoe models over 10 different topics (i.e., running economy, running performance, spatiotemporal parameters, ground reaction forces, joints stiffness, achilles tendon, plantar pressure, tibiofemoral load, foot strike pattern, and foot strike pattern, and joint coordination). With this review, runners and practitioners in the field that are concerned about selecting a suitable shoe for a performance, training, or an injury prevention functionality have clear information about the effects of the current shoe models and their specific features.

Keywords

Running shoes, running performance, running biomechanics.

1. Introduction

Nowadays, running shoes are characterized by the combination of several features with the aim of being useful for certain functions on the athlete ¹. For instance, shoe weight and longitudinal stiffness for improving running economy (RE), the upper construction and a varied midsoles hardness for improving comfort, or thinner midsoles and lower heel-toe drops for reducing injury risks have shown to be efficient features for the aforementioned functions ¹.

Based on their functions, several running shoe definitions have been purposed to create shoe categories (e.g., minimalist shoes, motion control shoes, cushioned running shoes) that represent the wide variety of shoe models constructed for the different purposes ². Regarding this, Ramsey et al.³ conducted a systematic review of the definitions and measurements tools used to describe footwear, highlighting the lack of consensus. Most of the studies reported a shoe type based on manufacturers' or customers' definitions, instead of assessing the different features embedded in it. The unique consensus achieved to assess shoe features and define them according to their properties are: (i) the minimal running shoe index purposed by Esculier et al.⁴, to define those footwear that simulate a barefoot running style, and (ii) the footwear total asymmetry score tool purposed by Ramsey et al.⁵, that defines the mediolateral control properties of running shoes.

In addition to the need to find a consensus about the definition of a running shoe based on the properties of its features, it is crucial to evaluate their effects on the runner to clearly understand its functionality on running performance and injury risk prevention. Regarding this, Richards et al.⁶ addressed this issue by summarizing the lack of evidence under the usual approach of prescribing "pronation control, elevated cushioned heel

running shoes” for distance runners with injury prevention or performance enhancement purpose. Despite this controversy, the American College of Sports Medicine addressed some conservative recommendations about how to select an appropriate running shoe based on having a minimal heel-to-toe drop, having no motion control or stability components, being lightweight, and discarding them when they get wear patterns that reveal the underneath sole layers ⁷.

The continuous innovations in the field create the need of evaluating the wide variety of shoe models that are being constructed for the same function. A clear example of this aspect is the work conducted by Squadrone et al.⁸ where they analyzed the acute effect of different shoe models defined as minimal shoes on the foot strike pattern (FSP) of rearfoot strikers (RFS). The magnitude of the alteration experimented was different across the wide variety of minimalist shoe models used, with those with less material and cushioning under the heel experiencing the greatest shift towards a midfoot strike (MFS) ⁸. Another example of the different effects caused by shoe models included in the same shoe category are the ones created as marathon racing shoes to improve the RE ⁹. Recently, as part of the “Breaking2” project, several innovations in the marathon shoes were introduced as a way to improve running performance compared to most commonly shoe models ¹⁰. Different weights, midsole properties, and longitudinal stiffness were the main influencing factors on the RE ⁹.

Based on the aforementioned, this systematic review aims to summarize the effects of the current shoe models under each shoe category over the RE, biomechanics, and performance of trained athletes. Due to the lack of consensus regarding what can be defined as a running shoe category, only studies that reported the brand, model and the main features of comparison were included. This was in order to provide runners,

coaches, and other practitioners with clear information on the effect of running shoes for racing, training, and injury preventing.

2. Methods

The elaboration of this systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.¹¹

2.1 Eligibility criteria

Study eligibility criteria were done following the PICO strategy (i.e., Population: Trained athletes; Intervention: Running shoes; Comparison: Shoe conditions; Outcome: Running economy, performance or biomechanics). Reports with a cross-sectional and intervention design that were published in peer-reviewed journals in English language within the last 5 years were of potential interest.

2.2 Information sources

Electronic databases including Web of Science, SPORTDiscuss, PubMed, and Scopus were used to identify studies from 2015 to the present. Footwear Science Journal was also used as an information source for this review as indicated by previous reviews relative to the topic¹². The search was limited to full-text availability. Search databases alerts were active from 01/01/2021 to 13/10/2021.

2.3 Search

The terms used for each item description were combined with “AND” and “OR” commands respectively on each database searcher: (Run*) AND (Shoe* OR Footwear OR Racing Flats OR Spikes) AND (Economy OR Energy Cost OR Metabolic Cost OR Energy Expenditure) AND (Time OR Race OR Speed OR Pace) AND (Efficiency OR Biomech* OR Kinetic OR Kinematic OR Spatiotemporal).

2.4 Study Selection

A general search was done to cover any type of runner and running shoes available in the scientific literature from 2015 to the present. After screening all records based on title and abstract, a full-text access of those studies that were of potential interest was done to apply a filter based on the criteria established by Hoitz et al.¹ to define the sample of runners that are immersed in a certain level of fitness and training routine (i.e., ≥ 3 years of running experience; > 3 training sessions/week; > 30 kilometers/week; < 18 minutes in 5km; < 35 minutes in 10km; < 3 hours in marathon). A second filter was applied based on the brand and model of the running shoes used (i.e., it must be specified).

2.5 Data Collection Process

Two independent researchers (SARA and AMM) performed the data extraction from reports in search of participants' characteristics, brand and model of the footwear used, testing protocol, outcomes of interest, and difference in means between shoe conditions. When there was a discordance between researchers, the case was exposed to a third one (VMSH) to reach a final consensus.

2.6 Quality assessment

For cross-sectional studies, a modified version of the Quality Index developed by Downs and Black¹³ was used. This modified version assesses the reporting quality (Item 1,2,3,6,7,10) as well as the internal (Item 22, 23, 25) and external validity (Item 12, 15, 16, 18, 20) of the studies. For intervention studies, the Physiotherapy Evidence Database (PEDro) scale was used.¹⁴ Two independent raters (SARA and FGP) performed the quality assessment. When the quality scores differed between raters, a third rater (VMSH) was consulted to reach a final consensus.

3. Results

A total of 2,991 articles after removing duplicates were screened based on title and abstract. Based on the selection criteria, 36 full-text articles were included in the quality analysis (figure 1).

Fig. 1 Flow diagram of study selection

Based on the quality assessment, none of the 36 articles were excluded (Table 1 and 2).

Table 1 Modified Downs and Black Quality Index (For cross-sectional studies)¹³

Table 2 Physiotherapy Evidence Databsase (For Intervention studies)¹⁴

From the 61 shoe models evaluated in the 36 articles recruited, the minimal running shoes (36%) category got the greatest interest in the field of running shoe research, followed by conventional running shoes (29.5%), maximal running shoes (11.5%), trail running shoes (8.2%), racing flats (6.5%), and marathon shoes (6.5%), and the track spikes (1.6%). The results of the different shoe models are presented according to the outcome measured in table 3.

Table 3 Running shoes index according to the outcome measured

A total of 11 articles analyzed the effects of running shoes on running economy and performance. Those of interest are listed in table 3 and the results of the individual studies are summarized in supplementary material (SM) 1.

SM 1 Participants' characteristics, running shoes evaluated, protocol used, and results over running economy and performance

Relative to the studies evaluating the effects of running shoes on running kinetics, the several outcomes measured have been grouped in ground reaction forces, joints stiffness, achilles tendon, plantar pressure, and tibiofemoral load in SM 2.

SM 2 Participants' characteristics, running shoes evaluated, protocol used, and results over running kinetics

Relative to the studies evaluating the effects of running shoes over running kinematics, the several outcomes measured has been grouped in spatiotemporal parameters, foot strike pattern, vertical oscillation, joints coordination, and joints motion in SM 3.

SM 3 Participants' characteristics, running shoes evaluated, protocol used, and results over running kinematics

4. Discussion and Implications

This systematic review aims to summarize the effects of current shoe models in each shoe category and their specific features on RE, biomechanics, and performance. In this way, practitioners in the field, runners, and coaches receive a piece of practical information about the effect of racing and training shoes. To clarify the reading of the variables analyzed, 10 subheadings are established to discuss each of them.

4.1 Running Economy

In the attempt to break the 2-hour marathon barrier, Nike developed the Nike Vaporfly 4% (NV) which achieved a final time of 2:00:25 in Monza. This achievement created a growing interest in scientific research to understand the magnitude of its benefits on running performance. To determine it, Barnes and Kilding¹⁵ compared the NV against two well-known running shoes, the Adidas Adios Boost 3 (AB) used in the previous marathon world record, and the Nike Zoom Matumbo 3 (NZ), a track spike commonly used in long-distance events. Over a range of velocities (14-18 km/h), the NV increased RE (mlO₂/kg/min) by 4.20 ± 1.20 % and 2.60 ± 1.30 % on average compared to AB and NZ respectively.¹⁵ Similar results were obtained by Hoogkamer et al.⁹ for the same running velocities, but in this case, RE was defined as energy cost (EC) (W/kg) where the metabolic substrate was considered. The comparison was made between NV, AB, and another Nike racing flats, the Nike Zoom Streak 6 (NS)⁹. Again, NV reduced EC (W/kg) by 4.16 % and 4.01 % on average compared to AB and NS respectively⁹. Hunter et al.¹⁶ reinforced this benefit of NV over EC when compared the aforementioned running shoes at 16 km/h. The NV reduced VO₂ (ml/kg/min) by 2.77 % and 1.92 % compared to AB and NS respectively.¹⁶

The benefits that footwear can cause on running EC could be explained by analyzing each of its features. Relative to the compliance and resilience properties of the midsole, Hoogkamer et al.⁹ conducted a mechanical test in which a vertical force of 2,000 N was applied for 185 ms to each shoe. The NS, made of EVA (ethylene-vinyl acetate), showed a deformation of 6.1mm and an energy return of 65.5 %.⁹ The AB, made of TPU (thermoplastic polyurethane), had a deformation of 5.9 mm and an energy return of 75.9 %.⁹ Finally, the new foam PEBA (polyether block amide), presented in the NV, showed a deformation of 11.9 mm and an energy return of 87 %.⁹

Regarding the weight, Hoogkamer et al.¹⁷ examined the effect of adding 100g and 300g to the Nike Zoom Streak 5 model. The authors revealed a linear regression of +1.11% EC (W/kg) per +100g in each shoe for a running velocity of 12.6 km/h¹⁷. When the weight effect is controlled, midsole properties could be the key for reducing the EC as Dinato et al.¹⁸ showed when comparing the effects of the Nike Free 2 and the Adidas Energy Boost for matched weights, finding a reduction of 2.4 % for the Adidas model. Furthermore, midsole properties seem to have a greater weighting factor in the overall EC as Warnes et al.¹⁹ showed with the comparison between the conventional shoes Asics Gel Cumulus 2012, of 400g of weight, and the minimal shoes Vibram Five Finger KSO, of 150g of weights, finding no significant differences between them at a running velocity of 11km/h. Barnes and Kilding¹⁵ also reinforced this finding by comparing the NV marathon shoes with the NM track spikes. Despite the reduced weight (NM vs. NV -87g), the NM increased the EC (mlO₂/kg/min) by 2.6 ± 1.3 % attributing this difference to the combined effect of the midsole properties and the curved carbon fiber plate for a range of velocities 14-18 km/h¹⁵.

The use of carbon fiber plates aims to reduce the dissipation of mechanical energy at the metatarsophalangeal joint by reducing its range of motion ²⁰. However, the ankle joint could be also altered by an increase of its push-off moment due to a greater lever arm ²⁰. This causes a change in the gear ratio between the external and internal ankle moment resulting in a reduction of the ankle angular velocity ²⁰. This reduction optimizes the plantar flexor force-length and force-velocity profile by reducing the total length change during the strike and the mean shortening velocity, which allows the triceps surae muscle units to operate in a more favorable position reducing their metabolic demands ²¹. Varied results have been found on the effect of increasing longitudinal stiffness on the EC (-3 % to +3 %) being the running velocity and runner characteristics the main causes underlying this variance ²⁰. Regarding this, Day and Hahn ²² increased the longitudinal stiffness of the Nike Epic React Flyknit model by inserting carbon plates creating a normal (5.9 Nm/rad), stiff (10.5 Nm/rad), and very stiff condition (17.0 Nm/rad). Subsequently, a group of 10 males competitive athletes ran at 14 and 17km/h, finding no improvement in any speed for the very stiff condition, and similar values for the stiff when compared to the normal condition ²². In addition to the added weight per plate (+50g), obtaining benefits from this feature needs to take into account the athlete's plantar flexor force-velocity profile and the running velocity to be used.

Lastly, another point of interest related to running shoes and EC is how they can delay its deterioration caused by fatigue. To test this, Vercruyssen et al. ²³ assessed the RE of a group of 13 competitive male runners previously and after finishing a trail running course of 18.4km, with uphill and downhill segments of 2000m of 13 % and -9 % of gradient using the minimal Salomon Sense model, the traditional model Salomon XT Wings, and another pair of Salomon Sense with matched weights to the XT Wings model (+122g). The EC was deteriorated to a greater extent when using the minimal model

compared to the traditional one despite showing lower values both pre and post completing the trail course ²³. Despite the differences shown in the EC, no significant differences were found in the final times to complete the trail course in each shoe condition, remaining the need to analyze their effect in longer trail courses ²³.

4.2 Running Performance

The transfer of EC reduction to running performance seems to be conditioned by the running distance. Regarding this, Dinato et al. ¹⁸ compared the Adidas Energy Boost with the minimal shoes Nike Free Run 2 with matched weights at a running velocity of 12km/h, finding a reduction in EC (VO₂ml/kg/min) of 2.4 % for the Adidas model. The athletes then performed two 3-km time trials with each shoe obtaining no significant differences in the final times (AB= 11:40 ± 62 sec NF= 11:49 ± 61 sec) ¹⁸. The authors concluded that this reduction in EC by the midsole properties would be significant in longer distance events (≥ 5km) where glycogen depletion is a limiting factor ¹⁸. Sinclair et al. ²⁴ compared the substrate utilization while running in the Vibram Five Fingers EL-X minimal shoes with the Adidas Energy Boost marathon racing shoes with equal weights at a running velocity of 13km/h. A lower carbohydrate utilization of 3.5 % on the Adidas model supports this hypothesis ²⁴. Regarding this, Vercruyssen et al. ²³ tested the EC of a group of 13 male competitive runners wearing the Salomon Sense and the Salomon XT Wings trail shoes during a level run at 10km/h and an uphill run at 9km/h, finding a 4.83 % and 2.36 % reduction respectively in benefits of the Sense model. This did not account for a significant difference in the time required to complete a customized trail course of 18.4km (SS= 01:51:27 ± 00:11:11 SXT= 01:51:07 ± 00:07:25) with uphill and downhill segments of 2000m of 13 % and -9 % of gradient ²³. It seems that the ingested carbohydrate gels and fluid intakes they standardized to complete the trail course in each footwear condition may reduce the potential benefits of the Salomon Sense model on EC.

The only improved performance due to a reduction in EC was founded in the work conducted by Hoogkamer et al.¹⁷ in which the effects of adding +100g and +300g to Nike Zoom Streak 5 racing flats were tested. An EC deterioration of +1.11%/+100g was transferred to a time penalty of +0.78%/100g in a 3000m distance race¹⁷. It can be concluded that the benefits on EC and its transfer to running performance depend on the features of the footwear and the distance of the race, being this transfer enhanced by the midsole properties for long distances, and by the reduced weight of the shoe for short distance races.

4.3 Running Biomechanics

4.3.1 Spatiotemporal Parameters

Certain running biomechanical patterns have been promoted as enhancers of RE but the current scientific literature is inconsistent in this relationship²⁵. Regarding spatiotemporal parameters, reducing the fraction between contact time and step time, defined as duty factor, has been hypothesized as an efficiency pattern since it promotes the storage and release of elastic energy of muscle-tendon units²⁵. However, this could condition the force-velocity profile of the triceps surae muscle units and, consequently, the muscle-metabolic mechanism. Beck et al.²⁶ analyzed the effect of producing soleus contractions on a fixed dynamometer during long, medium, and short durations for the same target average force. The reduction of the available time involved a greater peak muscle force production, which required a greater total active muscle volume, and which explained the increase in metabolic rate found²⁶. In a more ecological context, Lussiana et al.²⁵ compared the EC of a group of well-trained runners categorized into high and low duty factors groups over a range of velocities (10-12-14km/h), finding no significant differences between them.

From an injury prevention perspective, Bonnaerens et al.²⁷ demonstrated in a group of recreational runners, that those with higher duty factors experience lower external forces than those with lower duty factors for the same speed. The authors state that these results could constitute an interesting guideline to prevent overuse injuries, especially, for those runners who tend to experience an imbalance between the load exposure and the individual load capacity²⁷.

Based on the aforementioned effects of duty factor on running performance and injury risk, knowing how running shoes can modulate it according to their different characteristics could constitute a practical view on the functionality of each shoe category. Regarding this, Francis et al.²⁸ compared the effects of running unshod and shod with the New Balance MR350WR at 11 km/h on stride length (m) in a group of well-trained middle-distance runners. Under the rationality that the greatest training volume conducted by these types of athletes is under the lactate threshold, the choice of a running shoe that promotes a higher duty factor could constitute an efficient strategy to prevent overloads injury risks²⁷. Francis et al.²⁸ showed that athletes had a varied response, increasing, maintaining, and reducing stride length (m) in a wide percentage (-25 % to +5 %), leading to the conclusion that shoe prescription should consider the individual needs and characteristics of the users.

Relative to the individual needs, sex and age can influence the force-velocity profile of the plantar flexors muscles, being this reflected in the modification of spatiotemporal parameters such as longer contact times and shorter flight times for a given speed. Thus, the choice of a proper footwear could follow different strategies, for example, as a training tool for those that enhance the inverse spatiotemporal relationship, or as a performance tool for those that maintain the habitual pattern. Regarding this, Gijon-Nogueron et al.²⁹ evaluated a group of female endurance runners at 8, 12, and 15

km/h while wearing the Brooks Pure Cadence 6 and the Brooks Ghost 10, which differs primarily in their heel-to-toe drop (4 mm vs. 12 mm, respectively). Although they found no significant differences, the trend was a reduction in contact and flight times when using the 12 mm heel-to-toe drop model, and an increase in contact time and flight times for the 4 mm model ²⁹. As mentioned, the force-velocity profiles of runners' ankle flexors could be fixed in certain shoe models according to an intended functionality ²⁹.

This concept that running shoes can be used as a training or performance tool can also be reflected in the results obtained by Lussiana et al. ³⁰ and Lussiana et al. ³¹. In these works, a group of recreational runners was tested while running at 10km/h over a range of positive and negative gradients (-8 % to +8 %), wearing the Merrel Trail Glove minimal model, and the Salomon XR Mission and Salomon Speedcross 2 trail shoe models ^{30,31}. In the protocol used by Luissiana et al. ³¹, the randomized level orders and the 5 minutes rest between the 10-min trials reduced the potential fatigue effect. The results obtained reflect that running with the minimal model promoted shorter contact times and longer flight times for the different gradients ³¹, being a useful training method to consider. In the protocol used by Lussiana et al. ³⁰, authors induced substantial fatigue by using bouts of 50-min. The results obtained showed that in the early periods, minimal shoes promote a reduced contact time and longer flight times changing this pattern to equal contact times and shorter flight times for the final periods ³⁰. The magnitude of these changes associated with the running shoe can be modulated according to their varied features. Within the minimal category, Squadrone et al. ⁸ showed the varying effect of six different shoe models concluding that the magnitude of the adaption is dependent on the heel height and the absorption capacity of the shoe.

4.3.2 Ground Reaction Forces

Ground reaction forces (GRF) have received much attention from running shoe companies on the basis that altering GRF could potentially reduce injury risk and improve performance. Interpreting GRF as the result of body mass deceleration during the contact phase ($F=m*a$), these are conditioned to the spring-mass mechanism that runners adopt according to the contact surface ³², the FSP that modulate the initial mass that is being decelerated, and the midsole properties that interfere between the foot and the ground ³³.

Over a compliant surface or midsole material, runners show lower extremity movements to maintain constant the bouncing of the center of mass, and as a result, the runner's mass is decelerated in a shorter time producing a greater peak force ³². Regarding this, Kulmala et al. ³⁴ evaluated the effect of using varied midsoles thickness by comparing the Hoka One One Conquest maximal model (Heel: 43 mm; Forefoot: 37 mm), and the Brooks Ghost 6 conventional model (Heel: 33 mm; Forefoot: 22 mm) on the impact peak experimented in a group of RFS runners while running at 10 and 14.5 km/h. The use of the maximal model implied a higher impact peak due to the increased stiffness of the runners which is contrary to the functionality for which the maximalist footwear was created ³⁴. Kulmala et al. ³⁴ also justify that the properties of the midsole material could be a more determinant factor than the thickness of the midsole in the runner's lower limbs stiffness ³⁴. The combination between midsole thickness and midsole properties were evaluated by Da Silva et al. ³⁵, where they tested the effect of the New Balance 759 (Heel height: 45 mm), 890 (Heel height: 40 mm) and, Minimus MR10BG (Heel height: 25 mm) shoe models on the impact peak experimented by a group of RFS. The 890 model, considered by the manufacturer as a transitional shoe, represented an intermediate mechanical load between the conventional model 890 and the minimal model MR10BG

³⁵. The 890 and MR10BG shoe models had the same midsole materials, which means that an ideal midsole thickness could exist for this function of reducing mechanical loads.

Other factors also modulate the magnitude of the impact load experienced. Running barefoot or in minimal shoes involves the adoption of a non-heel strike (NHS) what modulates the portion of the total bodyweight that is being decelerated to zero during the impact phase, also called effective mass ³³. Thus, if the running shoe implemented enhance that change, the mechanical load experimented would be reduced. That is what Sinclair et al. ³³ tested in a group of RFS using the New Balance 1260v2 conventional model, and the Vibram Five Fingers M108, Inov-8 Evoskin, and Nike Free 5.0 minimal shoe models. Since none of the runners modified their FSP, the mechanical load experimented in the conventional model was less than in the minimal shoe models due to the midsole cushioning interference ³³. Since the FSP seems to require several weeks, there is a need to consider it as a selection criterion for further conclusions together with the participants' experience wearing a certain type of footwear. Regarding this, Sinclair et al. ³⁶ established two groups of habitual and non-habitual minimal shoe users to test them while wearing the New Balance 1260v2 conventional model, and the Vibram Five Fingers ELX minimal model. The habitual group experienced a reduction in the effective mass wearing the minimal model mainly explained by a reduction in the limb stiffness and an increase in the strike index ³³. Meanwhile, the non-habitual group experienced an increase in the effective mass without altering their mechanics, which reinforces the need for the midsole cushioning interference ³³.

From a performance perspective, the action-reaction force profiles of the current midsole materials could explain part of the recent improvements over RE ⁹. Knowing the force-displacement profile and the percentage of energy return of the midsoles materials, the negative and positive compression work rate (W/kg) can be calculated for a given

running force ($W=F \cdot d$) and step frequency. That is what Hoogkamer et al.³⁷ did in a group of competitive runners using the marathon shoes Nike Zoom Streak 6 (6.1 mm; 65.5 %), Adidas Adizero Adios Boost 2 (5.9 mm; 75.9 %), and the Nike Vaporfly 4% (11.9 mm; 87 %) at a running velocity of 16 km/h. Hoogkamer et al.³⁷ stated that the loading rate does not affect the midsole mechanical properties with the peak vertical force and the step frequency being the only factors that modulate the compression energy return rate. Therefore, concerning the aforementioned, an increase of the peak vertical GRF caused by an increase in stiffness or by a shift to a RFS promoted by the use of maximal shoe models may enhance the benefits of the resilience midsole.

4.3.3 Joints Stiffness

Joints work corresponds to how runners' lower limbs react to GRF. The main variables used to represent this aspect are vertical stiffness, leg stiffness, and torsional or joint stiffness³². These reflect the displacement of the center of mass, the leg length, and the change in joint angle during the stance phase, respectively³². The use of certain types of footwear can modify each of the aforementioned and this has a direct implication on performance and injury risk.

From a performance perspective, an increase of the lower limb stiffness has been shown to enhance RE due to the improvement of the stretch-shortening cycle³². Runners tend to keep constant the bounce of the center of mass, so an increase in peak vertical GRF is the main cause of the increased stiffness. That is what Lussiana et al.³¹ showed to involve the use of the Merrel Trail Glove minimal model compared to the Salomon Speedcross 2 trail model over a range of gradients (-8 to +8 %) at 10 km/h. The change of the maximum force was mainly explained by the reduced contact time and the increased flight time experimented with the minimal model³¹.

Another point of interest in stiffness is the running velocity since this one is increased to resist the higher peak forces associated with higher velocities ³². Thus, the selection of those running shoes that enhance stiffness at higher velocities is an important aspect to consider for a performance purpose. Regarding this, Kulmala et al. ³⁴ demonstrated that running with the Hoka One One Conquest maximal model compared to the conventional model Brooks Ghost 6 increases the leg stiffness at a running velocity of 14.5 km/h compared to the similar values experimented at 10 km/h. From these results, it could be interpreted that running shoes, from a performance perspective, are distance and velocity-dependent.

This seems to be also a key aspect for long-distance running, where deterioration of stiffness due to fatigue is related to a decrease in RE ³². Thus, finding a running shoe that enhances stiffness or delays its loss is a key performance issue. Lussiana et al. ³⁰ addressed this topic by giving to a group of 13 recreational males runners the Merrel Trail Glove minimal model, and the Salomon XR Mission trail model to complete a 50 min run on a treadmill at 65 % of their maximal aerobic velocity with varied gradients (-5 to +5 %). The decrease of leg stiffness with the minimal model was greater than the decrease in leg stiffness with the trail model, in part, due to the greater ankle joint excursion inherent in the use of minimal shoe models as Sinclair et al. ³⁸ demonstrated to involve in a wide variety of them. From a store and release elastic energy return reason, a forefoot strike (FFS) enhanced by these minimal shoe models could represent an efficient strategy, but it seems that this requires a greater muscle implication that matches the overall metabolic cost to the experimented with a RFS ³⁹. This one promoted by the use of maximal shoe models may be an appropriate strategy to delay the decrease of RE due to ankle muscle-tendon units fatigue in long-distance runs.

Relative to injury risk, an alteration in the lower limb stiffness has been shown to affect the different tissues under stress³². An increase in stiffness is related to an increase of peak forces, resulting in greater bones stress³². A decrease in stiffness involves greater joints excursion which increases in this case the soft tissue stress³². The stress-recovery process is commonly unbalanced by athletes throughout the season leading to an injury event. To avoid this, a common practice in the athlete community is to alternate the running shoes used throughout the week for the same type of session avoiding what James⁴⁰ termed reduced variability-overuse injury. In this way, it is hypothesized that lower limbs muscle-tendon units experience different stimulations avoiding in this manner an excessive load that would unbalance the stress-recovery process of a certain muscle-tendon unit. By analyzing the negative joint work as a reflection of eccentric muscle activity, it can be determined whether running shoes create different stimulations. Borgia and Becker⁴¹ and Garofolini et al.³⁹ showed that maximal shoe models tend to decrease the ankle negative joint work compared to the minimal shoe models. The lower strike index in the maxima shoe models explains this aspect in which the GRF vector acts closer to the ankle joint, producing a reduced joint moment to resist and relaying this force absorption on the knee and hip joints.

4.3.4 Achilles Tendon

The triceps surae acts by the confluence of the force produced by the gastrocnemius and soleus muscles, transmitted through the Achilles tendon (AT) towards the posterior area of the calcaneus allowing the plantar flexion action⁴². The load that the AT receives is an important aspect to consider to enhance its adaption to exercise by finding the balance between collagen synthesis and degradation⁴². This can be modulated by the type of footwear used and its effects on AT stressors such as contact time, stride frequency, and the peak force experimented⁴².

Relative to the peak force, Sinclair et al.⁴³ and Sinclair et al.⁴² showed that running in conventional shoe models like the New Balance 1260v2 and the Saucony Pro Grid Guide II, involved a reduced peak force of the triceps surae muscle-tendon unit compared to barefoot running. The increase in ankle joint torque promoted by the NHS characteristic of minimal shoes and barefoot running explain these results. On the basis that runners that progress toward maximal shoe models could reduce their AT stress, Sinclair et al.⁴⁴ compared the Hoka One One Goleta against the New Balance 1260v2 conventional model and the Vibram Five Fingers ELX minimal model in a group of recreational runners with a RFS. Consistent with previous studies, the maximal model supposed a reduction in AT stress compared with the minimal model, but not with the conventional one suggesting that an oversized midsole characteristic of this shoe category is not required to achieve this reduction⁴⁴.

In addition to the peak forces experimented, the occurrence of an Achilles tendinopathy depends on the frequency of the load exposure⁴⁴. This point is of great relevance since minimal shoes tend to decrease contact times and increase stride frequency, thus a more accurate overall load can be quantified by taking these factors into account. To assess this, Sinclair et al.⁴⁴ determined the AT force impulse by multiplying the AT force by the stance phase, and then, by the number of steps required to complete a mile. Finally, the AT per mile remained higher in the Vibram Five Fingers ELX minimal model, than the New Balance 1260v2 conventional model, and the maximal model, Hoka One One Goleta.

Knowing that minimal shoes involve high AT stress, it is necessary to have a comprehensive view of how runners adapt to this type of footwear. Joseph et al.⁴⁵

evaluated this aspect by introducing to a group of males and females habitually shod runners, the use of the Newton Gravity minimal model. They were asked to use this model to complete part of their overall mileage run per week, progressing from 10% for the 1st week, to 100% for the 11th week. The AT increased the cross-sectional area and stiffness in response to the increased load ⁴⁵. However, these changes were observed acutely in male runners, whereas female runners seem to require more weeks to obtain a significant response ⁴⁵.

4.3.5 Plantar Pressure

Based on the assumption that the development of a running injury occurs due to the magnitude of the forces acting on the musculoskeletal system, it is believed that the cushioning of a running shoe that redistributes these forces can reduce this risk. This is the main reason why several authors compared the effect of minimal and maximal shoes on the plantar pressures experienced in the forefoot, midfoot, and rearfoot regions. The general conclusion of this comparison is that when wearing minimal shoes, runners tend to an NHS that increases the plantar pressure over the forefoot region ^{46,47}. This shifted FSP depends on the runners' experience with this type of footwear since those who are not familiar with it require several weeks to do so ³⁶. Another conditioning factor is the distance to be covered since runners wearing minimal shoes tend to a RFS when the triceps surae gets fatigued ³⁰. In these cases, the lack of the cushioning properties of a midsole would increase the risk of developing a stress fracture in this region. On the other hand, in those cases in which the changed FSP induces an increase of pressure in the forefoot region, the increased risk of injury to these structures will be more predominant ⁴⁶. Other authors purpose that this increased stress could involve a stimulation of forefoot muscle growth ⁴⁷.

This capacity of a shoe to redistribute forces is conditioned by the kilometers of use. Regarding this, Escamilla-Martinez et al.⁴⁸ assessed the plantar pressures distribution of a group of distance runners wearing the New Balance 738 after 0, 350, and 700 km of use. The greatest deterioration was found in the forefoot region as a result of the higher loads applied during the propulsive phase where the crushing of the midsole cells involved an increase of the forefoot pressure⁴⁸. From this lifespan measurement, the authors concluded that the New Balance 738 is effective in maintaining the original maximum pressures up to 700 km of use.

From a performance perspective, an increase in plantar pressures could involve a deterioration of the RE due to its strong relationship with perceived comfort⁴⁹. Thus, the functionality of a running shoe seems to be strongly conditioned to the preservation of midsole properties.

4.3.6 Tibiofemoral Load

The magnitude and frequency of tibiofemoral loads are considered strong knee injury risk predictors^{43,50,51}. These can be modulated by the runners' FSP, where a greater plantarflexion could reduce the knee range of motion, and consequently, increase the tibiofemoral contact area⁵⁰. Running with minimal shoes elicits this NHS which could represent a potential way to reduce the tibiofemoral stress. To assess this, Sinclair⁵⁰ evaluated a group of RFS using the Vibram Five Fingers ELX minimal model and the New Balance 1260v2 conventional model. Non-significant differences were found between shoe conditions, which could be explained by the runners' lack of familiarization use with the minimal shoes and the need for more time to implement a change in their FSP⁵⁰. In a second study, Sinclair⁴³ contrasted this change in FSP in a group of RFS when running barefoot, but it was not enough to alter the knee kinematics. Despite this, a

significant increase in medial and lateral stress was found as a reflection of the increased instantaneous loading rate ⁴³. The medial tibiofemoral region seems to be more prone to osteoarthritis development due to the higher forces experimented ⁵¹. Sinclair et al. ⁵¹ evaluated this aspect for different minimal shoe models by determining the knee adduction moment as a pseudo-measure of medial tibiofemoral loading. Using the statistical parametric mapping procedure, an increased medial tibiofemoral stress in the early stance phase was found for the Nike Free 5.0 and the Inov-8 Evoskin minimal shoe models (15-30 %) compared to the New Balance 1260v2 conventional model ⁵¹. The increased vertical ground reaction loading rates could be the underlying reason for this increase ⁵¹. From these results, the authors conclude that barefoot and minimal footwear may increase the risk of injury to the tibiofemoral medial region ⁵¹.

4.3.7 Foot Strike Pattern

As mentioned previously, the FSP can modify several aspects of the runner such as RE due to the alteration of the triceps surae muscle activity, the duty factor due to the length of contact time and force-time application profile, the GRF due to the alteration of runners' stiffness, or tibiofemoral stress due to the degree of knee flexion and contact area induced by the FSP adopted.

RFS, MFS and FFS can be adopted with the use of a certain type of footwear ⁵². This relationship between minimal shoes and FFS is well established but the wide variety within this category produces different results according to their different features. Regarding this, Squadrone et al. ⁸ showed that the New Balance MR00GB, the Inov 8 Bare-X 200, and the Vibram Five Fingers Seeya shoe models achieved a similar pattern to a barefoot condition, while the Newton Running MV2, the Nike Free 3.0, and the Saucony Kinvara 2, reduced the foot strike index (%). Chan et al. ⁵³ found that those

runners who presented a RFS and NHS maintained their strikes either using the Adidas Adizero Boost marathon model and the Hoka One Clifton 3 maximal model, concluding that other factors also influence the strike transition such the habitual type of footwear and the familiarization time for runners to a new condition. In this case, the runners had no experience using the shoe models assessed and a familiarization period of 4 minutes⁵³. Sinclair et al.³⁶ showed that the transition from the New Balance 1260v2 conventional model to the Vibram Five Fingers ELX minimal model did not result in a significant change to an NHS to those runners who are not habitual users of minimal shoes. As Au et al.⁵⁴ showed, the running experience for one month with the running shoe under evaluation may imply a different response than the one presented in the immediate use⁵⁴.

4.3.8 Joint Coordination

Joint coordination has been defined as a way to determine the runner injury risk according to the variability and coupling presented^{55,56}. James⁴⁰ purposed the concept of variability-overuse injury to define the idea that a stiff pattern involves the overloading of certain tissues sites, which would involve the increase of injury risk. Relative to joints couplings, certain patterns have been identified as detrimental for the runners' musculoskeletal health such as prolonging the subtalar eversion beyond the peak knee flexion, which increases the knee stress due to the opposite torques acting on the proximal and distal ends of the tibia⁵⁶.

This concept has been of interest to assess the effects of the new trend of using maximal shoes in the running community. It is hypothesized that the oversized midsole particular of this type of footwear can dampen the haptic feedback that informs about the subsequent movement executions, consequently altering the joint coordination⁵⁵. To assess this, Prejean and Ricard⁵⁵ and Borgia et al.⁵⁶ used the maximal shoe models, Hoka

One One Stinson and the Hoka One One Bondi 4 to contrast this hypothesis. With these maximal shoe models, the runners had similar movement patterns to those presented in footwear with a lower thickness. A theory that can explain these results is the preferred movement path paradigm purposed by Nigg et al.⁵⁷. These authors state that runners tend to maintain a certain movement path as this is the most efficient way that the neuromuscular system has to develop it⁵⁷. If an external factor interferes with this preferred path (i.e., orthotics, running shoes), muscle activity will be increased to preserve this pattern⁵⁷.

5. Conclusion

With this review, runners and practitioners aware of the selection of a suitable running shoe for a performance, training, or injury risk prevention functionality have clear information about the effects of current shoe models and their specific features for such purposes. The continuous innovations in the running shoe field have created some shoe models that enhance the running economy. However, the transference to running performance across the different running distance competitions must be clarified. Based on the concept of variability-overuse injury, the thickness and properties of the midsole of the different shoe models can modify the stress on certain tissues by altering the foot strike pattern. In addition to an injury prevention purpose, runners and practitioners in the field could use those shoe models that increase or decrease certain tissue stress as an efficient training strategy. Future research should update the effects of the upcoming shoe models either comparing their general characteristics or the isolated contribution of each shoe feature. Determining their progressive properties deterioration should be also addressed which would give runners and practitioners in the field further insights of their daily training footwear.

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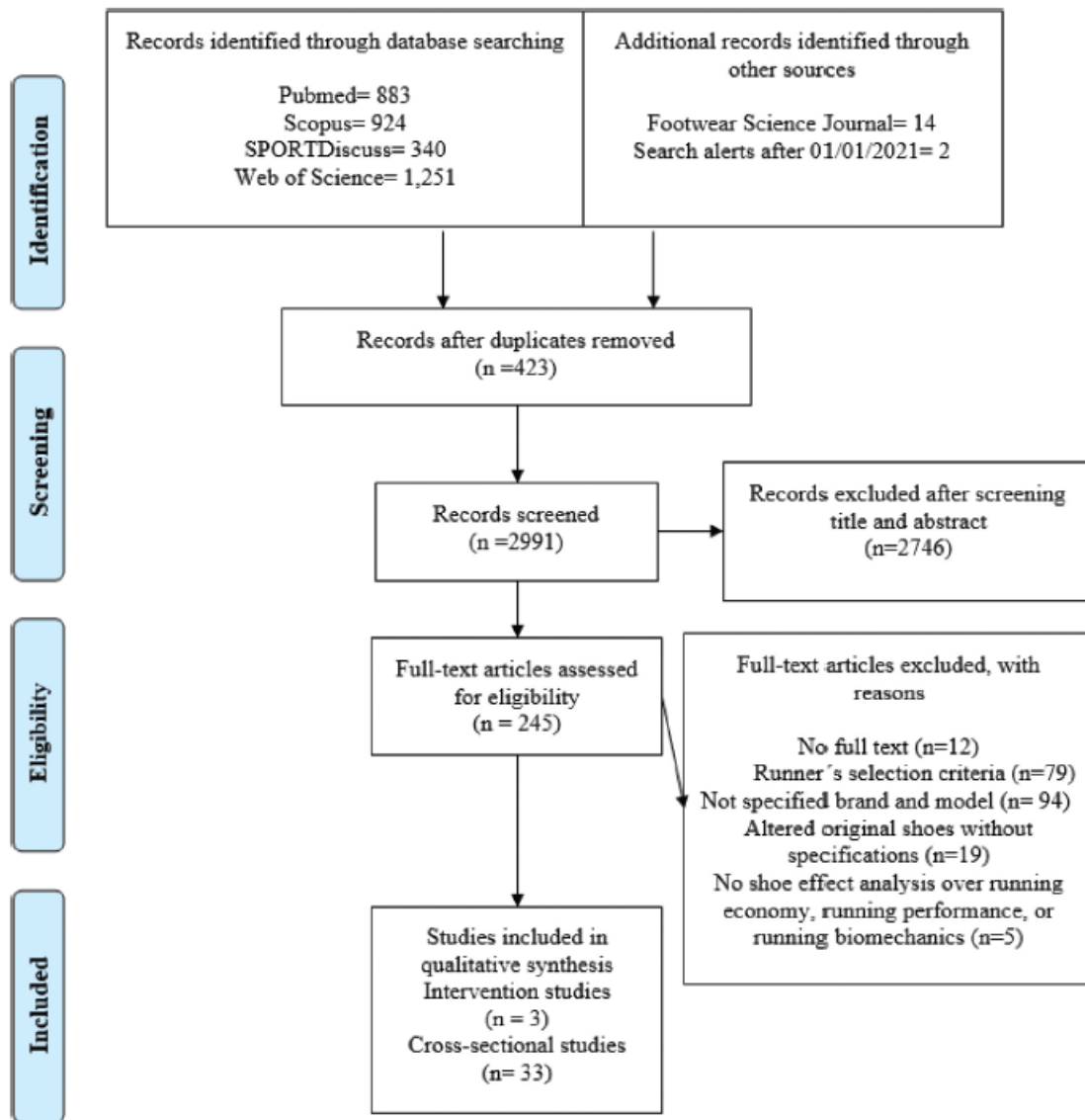


Figure 1. Flow diagram of study selection.

Table 1. Modified Downs and Black Quality Index (For cross-sectional studies) ¹³.

Reference	Items															Total
	1	2	3	6	7	10	12	15	16	18	20	22	23	25		
Barnes and Kilding ¹⁵	1	1	1	1	1	1	1	U	1	1	1	1	1	1	13	
Borgia and Becker ⁴¹	1	1	0	1	1	1	0	U	1	1	1	0	1	0	9	
Borgia et al. ⁵⁶	1	1	1	1	1	1	0	U	1	1	1	1	1	1	12	
Chan et al. ⁵³	1	1	1	1	1	1	1	U	1	1	1	1	1	0	12	
Da Silva ³⁵	1	1	1	1	1	1	0	U	1	1	1	0	1	1	11	
Day and Hahn ²²	1	1	1	1	1	1	1	U	1	1	1	0	1	0	11	
Dinato et al. ¹⁸	1	1	1	1	1	1	1	U	1	1	1	0	1	1	12	
Escamilla-Martínez et al. ⁴⁸	1	1	1	1	1	1	0	U	1	1	1	0	0	0	9	
Francis et al. ²⁸	1	0	1	1	1	1	0	U	1	1	1	0	1	0	9	
Garofolini et al. ³⁹	1	1	1	1	1	1	0	U	1	1	1	1	1	1	12	
Gijon-Nogueron et al. ²⁹	1	1	1	1	1	1	1	U	1	1	1	0	1	0	11	
Gillinov et al. ⁵²	1	1	1	1	1	1	1	U	1	1	1	0	1	0	11	
Hoogkamer et al. ⁹	1	1	1	1	1	1	0	U	1	1	1	1	1	0	11	
Hoogkamer et al. ³⁷	1	1	1	1	1	1	0	U	1	1	1	0	1	1	11	
Hoogkamer et al. ¹⁷	1	1	1	1	1	1	0	U	1	1	1	0	1	0	10	
Hunter et al. ¹⁶	1	1	1	1	1	1	1	U	1	1	1	0	1	1	12	
Jandová et al. ⁵⁸	1	1	1	1	1	1	0	U	1	1	1	0	0	0	9	
Jandová et al. ⁴⁷	1	1	1	1	1	1	0	U	1	1	1	0	1	0	10	
Kulmala et al. ³⁴	1	1	1	1	1	1	0	U	1	1	1	0	1	1	11	
Lussiana et al. ³⁰	1	1	1	1	1	0	0	U	1	1	1	0	1	1	10	
Lussiana et al. ³¹	1	1	1	1	1	0	0	U	1	1	1	0	1	0	9	
Ogston ⁴⁶	1	1	1	1	1	1	0	U	1	1	1	0	0	0	9	
Prejean and Ricard ⁵⁵	1	1	1	1	1	1	1	U	1	1	1	1	1	1	13	
Sinclair ⁵⁰	1	1	1	1	1	0	0	U	1	1	1	0	1	1	10	
Sinclair et al. ⁴⁴	1	1	1	1	1	1	0	U	1	1	1	0	1	1	11	
Sinclair ⁴³	1	1	1	1	1	1	0	U	1	1	1	0	1	0	10	
Sinclair et al. ⁴²	1	1	1	1	1	0	0	U	1	1	1	0	0	0	8	
Sinclair et al. ³⁸	1	1	1	1	1	0	0	U	1	1	1	0	1	1	10	
Sinclair et al. ⁵¹	1	1	1	1	1	1	0	U	1	1	1	0	1	1	11	
Sinclair et al. ³³	1	1	1	1	1	1	0	U	1	1	1	0	1	1	11	
Sinclair et al. ³⁶	1	1	1	1	1	1	0	U	1	1	1	1	1	1	12	
Squadrone et al. ⁸	1	1	1	1	1	1	0	U	1	1	1	0	1	1	11	
Warne et al. ¹⁹	1	1	1	1	1	1	0	U	1	1	1	0	1	1	11	

1: Yes; 0: No; U: Unable to determine

Table 2. Physiotherapy Evidence Databsase (For Intervention studies) ¹⁴.

Reference	Items											Total
	1	2	3	4	5	6	7	8	9	10	11	
Au et al. ⁵⁴	1	1	0	1	0	0	0	1	1	1	1	7
Joseph et al. ⁴⁵	1	0	0	1	0	0	0	1	1	1	1	6
Vercruyssen et al. ²³	0	1	0	1	0	0	0	1	1	1	1	6

1: Yes; 0: No

Table 3. Running shoes index according to the outcome measured.

Running Economy		
Adidas Adios Boost 2 ^{9,29}	Nike Free Run ¹⁸	Salomon Sense 48
Adidas Adios Boost 3 ^{15,18}	Nike Vaporfly 4% ^{9,15}	Salomon XT Wings ⁴⁸
Adidas Energy Boost ²¹	Nike Zoom Matumbo ¹⁵	Vibram Five Finger KSO ¹⁹
Asics Gel Cumulus 2012 ¹⁹	Nike Zoom Streak 5 ¹⁷	
Nike Epic React ²²	Nike Zoom Streak 6 ^{9,16}	
Running Performance		
Adidas Energy Boost ¹⁸	Nike Free Run 2 ¹⁸	Nike Zoom Streak 5 ¹⁷
Salomon Sense ²³	Salomon XT Wings ²³	
Spatiotemporal Parameters		
Barefoot ^{8,28}	New Balance MR00GB ⁸	Salomon XR Mission ³⁰
Brooks Ghost 10 ²⁹	New Balance MR350WR ²⁸	Saucony Kinvara 2 ⁸
Brooks Pure Cadence 6 ²⁹	Newton Running MV2 ⁸	Saucony Progrid Gruide ⁸
Inov Bare-X 200 ⁸	Nike Free 3.0 ⁸	Vibram Five Fingers Seeya ⁸
Merrel Trail Glove ^{30,31}	Salomon Speedcross 2 ³¹	
Ground Reaction Forces		
Adidas Adios Boost 2 ³⁷	New Balance 1260v2 ^{33,36}	Nike Free 5.0 ³³
Barefoot ^{33,35}	New Balance 759 ³⁵	Nike Zoom Streak 6 ³⁷
Brooks Ghost 6 ³⁴	New Balance 890 ³⁵	Nike Zoom Vaporfly 4% ³⁷
Hoka One One Conquest ³⁴	New Balance Minimus MR10GB	Vibram Five Fingers ELX ³⁶
Inov-8 Evoskin ³³	³⁵	Vibram Five Fingers M108 ³⁶
Joints Stiffness		
Brooks Ghost 6 ³⁴	Mizuno Wave Rider 21 ³⁹	Salomon Speedcross 2 ³¹
Hoka One One Bondi 4 ⁴¹	Mizuno Wave Sonic ³⁹	Salomon XR Mission 30
Hoka One One Conquest ³⁴	New Balance 1400v3 ⁴¹	Saucony Pro Grid Guide II 41
Inov-8 Evoskin ³⁸	Nike Air Zoom Pegasus 32 ⁴¹	Vibram Five Fingers ^{24,41}
Merrel Bare Access ³⁸	Nike Free 3.0 ³⁸	Vivo Barefoot Ultra ⁴¹
Merrel Trail Glove ^{30,31}		

Table 3. (Cont).

Achilles Tendon		
Barefoot ^{39,40}	New Balance 1260v2 ^{38,39}	Saucony Pro Grid II ⁴⁰
Hoka One One Goleta ³⁸	Newton Gravity ⁴⁷	Vibram Five Finers ELX ³⁸
Plantar Pressure		
Asics GT-2000 ³⁰	New Balance 738 ²²	Salomon XA PRO ³¹
Hoka One One Clifton 2 ³⁵	New Balance Minimus Hi-Rez ³⁵	Salomon XR Mission ³³
Merrel Trail Glove ³³	Nike Free 3.0 ³⁰	Vivobarefoot Primus ³¹
Tibiofemoral Load		
Barefoot ^{39,42}	New Balance 1260v2 ^{37,39,42}	Vibram Five Finger ELX ³⁷
Inov-8 Evoskin ⁴²	Nike Free 5.0 ⁴²	Vibram Five Fingers M108 ⁴²
Foot Strike		
Adidas Adizero Boost ¹⁸	New Balance M880v3 ²⁶	Nike Free 3.0 ⁸
Barefoot ^{8,26,46}	New Balance Minimus 10v2	Saucony Kinvara 2 ⁸
Double Coin Plimsolls ⁴⁶	Trail ²⁶	Saucony ProGrid Guide ⁸
Hoka One Clifton 3 ¹⁸	New Balance MR00GB ⁸	Vibram Five Fingers ELX ⁴⁴
Inov8 Bare-X 200 ⁸	Newline Runaissance 4.0 ⁴⁶	Vibram Five Fingers Seeya ⁸
New Balance 1260v2 ⁴⁴	Newton Running MV2 ⁸	
Joints Coordination		
Barefoot ³⁶	Hoka One One Stinson ³⁶	New Balance Minimus ³⁶
Hoka One One Bondi 4 ¹⁷	New Balance 1400v3 ¹⁷	Nike Air Zoom Pegasus 32 ¹⁷

**Artículo 2: Revisión narrativa del efecto de la
regulación de la World Athletics en el funcionamiento
del calzado y el rendimiento en carrera**

A Review of the Potential Effects of the World Athletics Stack Height Regulation on the Footwear Function and Running Performance

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Abstract

This review aims to synthesize and discuss the potential effects of a stack height modification on the function of the different footwear features and their effects on running performance. Peer-reviewed studies were identified from electronic databases using a structured keyword search and a screening process. Complementary sources were used to illustrate and discuss the current racing footwear constructions. With regard to the shoe mass, it is suggested that a stack height difference of 20 mm could induce a meaningful effect on performance. With respect to the midsole properties, it seems that reducing the stack height does not alter the energy returned, given that the lower midsole deformation is counteracted with an increased stiffness. However, it should be noted that this might affect the timing of the midsole deformation and restitution, which should be matched with the mid and propulsive stance phases. Lastly, the curved geometry of the forefoot sole needed to create the teeter-totter effect could be affected by the stack height reduction. However, current racing footwear designs have counteracted this modification by proximately placing the rocker axis and increasing the toe spring.

Keywords: running performance; running biomechanics; footwear technology

1. Introduction

The 2 h marathon barrier has been one of the greatest challenges in human physiology. Since 1950, the world record has been reduced by more than 16 min, with the improved athlete context as the potential cause of such progression (i.e., training programs, athletes monitoring, and socio-economic aspects) ¹. However, in 2016, the advances in footwear technology implemented for the breaking 2 h attempt marked a turning point in the natural progression of performance seen up to date ².

Breaking the 2 h marathon barrier required athletes to maintain a metabolic steady-state on a 2:50 min:s pace over 42.195 m. Considering the different performance determinants in long-distance running (e.g., maximum oxygen consumption, running economy, critical velocity) ³⁻⁵, it seems that an extraordinary combination of them was required to achieve such demand. In this regard, Jones et al. ³ defined the physiology of a group of top elite marathoners, displaying a peak oxygen uptake of 71.0 ± 5.7 mL/kg/min and relative oxygen consumption at 21 km/h of $95 \pm 5\%$ of the peak oxygen uptake ³. The metabolic steady state exhibited by the group was 20.2 ± 0.6 km/h, their lactate turn point (4.6 ± 1.3 mmol/L), where $92 \pm 3\%$ of the peak oxygen uptake was required with a cost of running of 188 ± 20 mL/kg/km ³. Due to the time limit at such running intensity, marathon times predictions from this evaluation were made by dividing the oxygen uptake (ml/kg/min) by the cost of running (ml/kg/km) at 96% of the lactate turn point ³. A time prediction of $2:08:31 \pm 03:48$ was found, with the best time being $2:00:01$ ³. At these performance levels, all the possible marginal improvements were contemplated for overpassing the 2 h target. In this regard, the marathon shoes released for this aim captured the attention of the running and scientific community. It was later published that compared to a previous world-record marathon shoe model, the prototype provided by Nike improved by 4% the running economy ⁶. Therefore, if an athlete of

2:03:40 displays an oxygen uptake of 65 mL/kg/min and a cost of running of 191 mL/kg/km (i.e., $60 \times 65/191 = 20.4$ km/h) at his marathon intensity (i.e., the lactate turn point)³, the 4% improvement would have placed his marathon pace on 21.2 km/h ($60 \times 65/183.4 = 21.2$ km/h) resulting in a final time of 1:59:34. Likewise, other external factors such improvements in the course design⁷ and pacing aids (i.e., shifting pacers, pacing car) were contemplated to increase the likelihood of success by improving the cost of running.

After the implementation of these footwear innovations (i.e., lightweight materials, compliant and resilient midsole, increased longitudinal stiffness, curved forefoot geometry) in the athletic community and the proven performance improvements in long-distance road events^{2,8}, the controversy of “technology doping” emerged, leading the World Athletics to create a shoe regulation for the different events based on limiting the stack height (i.e., the amount of shoe material between the foot and the ground) (Table 1)⁹. This regulation is being widely deliberated in order to ensure that performance is achieved via the primacy of human effort rather than technology in running shoes¹⁰⁻¹³. On the one hand, Burns and Tam¹⁰ suggested that limiting the stack height might be a solution as it would limit those footwear features that could enhance the running economy. Furthermore, this rule would also limit any future innovation that could jeopardize the integrity of athletics¹⁰. In response to such a proposal, Frederick¹¹ stated that there is a lack of evidence and consensus on the measurement of the stack height. Hoogkamer¹² supported these statements and mentioned that increasing the stack height results in no advantage in the running economy due to the increase in mass and instability. It was also added that the resilience property of the midsole (i.e., the capacity to store and to release the mechanical energy applied) of current midsole materials is not compromised by such limitation since the greatest deformations were found to be in 12

mm, needing just a few more mm to avoid the bottom out of the midsole, which could have affected the storing phase ¹². Nigg et al. ¹³ subsequently contributed to this debate by discussing the potential contribution of each shoe feature to the improvements in the running economy. The authors mentioned that the major effect of contemporary running shoes on running performance comes from the increased longitudinal stiffness and the forefoot rocker (i.e., the upward curvature of the forefoot sole) that generates the so-called “teeter-totter effect” ¹⁴.

-Table 1 about here-

Despite this stack height limitation, this rule was insufficient to avoid the great improvement in long-distance events that began with the running shoe revolution in 2017 ^{2,15}, which resulted in stricter regulation, being the stack height further reduced (Table 1) ⁹. Therefore, in order to clarify the potential effects of reducing the stack height, this scoping review aims to synthesize and discuss the potential effects of a stack height modification on the function of the different footwear features and their effects on running performance.

2. Materials and methods

The footwear features of potential interest for this review were first identified according to an expert consensus ¹⁶. Subsequently, these were chosen based on their potential impact on running performance ¹³, with specific attention to their susceptibility to being influenced by a reduction in the stack height (i.e., shoe mass, midsole properties, teeter-totter effect items). The Pubmed and Web of Science electronic databases were used to identify studies from inception to the present. Each footwear feature term was combined with different running footwear and performance terms using “AND” and “OR” commands: (Shoe* OR Footwear OR Racing Flats OR Spikes) AND (Mass OR

Midsole OR Longitudinal stiffness) AND (Economy OR Energy Cost OR Time OR Race OR Speed OR Pace). After removing duplicates and irrelevant articles, those with full-text availability were screened to identify if the footwear conditions compared in a running performance outcome (i.e., running economy, time trial, time to exhaustion) were created by a stack height reduction while maintaining the rest of the footwear features similarly. If not, those studies analyzing each footwear feature in isolation while controlling potential confounders on a running performance outcome were selected (Figure 1). The evidence provided by these studies was then discussed using complementary sources (see details in each section).

-Figure 1 about here-

3. Results

3.1 Effect of the stack height on running performance

Two studies were identified that analyze the effect of varying the midsole thickness on a running performance outcome while maintaining the rest of the footwear features similarly^{17,18}. This was performed by using the same footwear prototype with different midsole thicknesses and adjusting the shoe weight by adding lead beads.

3.2. Effect of the shoe mass on running performance and influence of the stack height

Three studies were identified that analyze the effect of the shoe mass on a running performance outcome while maintaining the rest of the footwear features similarly¹⁹⁻²¹. This was performed by adding lead beads to the same footwear model^{19,21} or to the feet²⁰. In order to illustrate the effects of reducing the stack height on shoe mass, a linear regression analysis was traced to the shoe mass and stack heights reported by Barrons et al.¹⁷ in Figure 2. In addition, the midsole thickness and shoe mass of 15 common racing

footwear models were searched on a specialized running footwear website ²² and reported in Figure 2.

-Figure 2 about here-

3.3 Effect of midsole properties on running performance and influence of the stack height

Four studies were identified that analyze the effect of the midsole properties on a running performance outcome while maintaining the rest of the footwear features similarly ^{18,28,23,24}. This was performed by using the same footwear prototype with different midsole stack heights ^{17,18} or materials ²⁴ and by running barefoot on a standard and cushioned surface ²³.

3.4 Effect of teeter-totter effect on running performance and influence of the stack height

A single study was identified that analyzed the teeter-totter effect on a running performance outcome while maintaining the rest of the footwear features similarly ²⁵. This was performed by comparing different racing footwear models with increased longitudinal stiffness of similar weights (<30 g) ²⁵. In order to further illustrate the potential implication of the stack height on the teeter-totter effect, the rocker and toe spring radius, as well as the rocker axis position, have been analyzed in different current racing footwear models using the Kinovea free-access software ²⁶ (Figures 3 and 4).

-Figure 3 about here-

Figure 4 about here-

4. Discussion

4.1 Effect of the stack height on running performance

Despite being a highly debated topic ¹⁰⁻¹³, the effect of stack height on running performance has been scarcely analyzed. The results provided by Barrons et al. ¹⁷ and Bertschy et al. ¹⁸ are the unique published data regarding this topic (See references for further details). On the one hand, Barrons et al. ¹⁷ compared four identical models differing only in the midsole thickness (i.e., 35, 40, 45, 50 mm). After matching shoe weights, no significant differences in running economy were observed. On the other hand, Bertschy et al. ¹⁸ compared three stack height conditions (i.e., 30, 40, and 60 mm) on two footwear prototypes with two different midsole materials (i.e., EVA and NITRO). After matching shoe weights, increasing the stack height in the EVA midsole material resulted in a 0.4% running economy penalty per 10 mm added ¹⁸. On the contrary, the NITRO material improved the running economy by 0.13% per 10 mm added ¹⁸.

Two relevant factors of these results should also be noted. On the one hand, the running economy would be impaired if the added shoe mass was considered. According to the 1% rule per 100 g added ^{20,21}, Bertschy et al. ¹⁸ reported that the running economy deteriorated by 0.5% per 10 mm for the EVA midsole material tested and by 0.34% per 10 mm for the NITRO midsole material. Likewise, the conditions tested by Barrons et al. ¹⁷ impaired 0.33% per 10 mm added. Therefore, according to the largest stack height limitation established (i.e., 20 mm), running on an illegal shoe of 40 mm would result in a 0.7 to 1.0% detriment in running economy from the shoe mass standpoint. On the other hand, the contrasting differences reported between the EVA (i.e., +0.4%/10 mm) and the NITRO material (i.e., -0.13% per 10 mm) when matching weights also revealed an interesting factor of this footwear feature ¹⁸. In this regard, Barrons et al. ¹⁷ analyzed the

force-deformation profile of the different stack height conditions made with the same midsole material, observing an increased vertical midsole deformation and a decreased midsole stiffness when increasing the stack height, which resulted in similar energy returned. Therefore, the different trends observed on the midsole material used by Bertschy et al.¹⁸ could be caused by other factors, such as the timing of the force-deformation profile with the ground contact time displayed by the athletes at the running speed tested (i.e., 14 km/h)¹⁸. However, it seems that any potential improvement caused by altering the midsole properties due to an increased stack height would be counteracted by the shoe mass (i.e., -0.13% vs. 0.34% per 10 mm). The potential role of these footwear features on running performance and the effect of the stack height on it is further discussed in the following sections.

4.2 Effect of the shoe mass on running performance and influence of the stack height

The effect of the shoe mass on running economy has been widely studied, finding a consistent linear increase of 1% per 100 g added^{20,21}. Likewise, its effect on a 3000-meter final time ($10:26 \pm 57$ s) has been established in a time penalty of $\sim 0.8\%$ per 100 g added (~ 50 s)²¹. In shorter efforts ($3:13 \pm 41$ s), Rodrigo-Carranza et al.¹⁹ reported a mean time penalization of ~ 12 and 22% (24 and 52 s) per 50 and 100 g added. Therefore, it seems that the increased internal work (i.e., the work performed to accelerate the body segments regarding the center of mass) causing this performance detriment is conditioned to the running velocity, taking a prominent role at higher ones²⁷⁻²⁹. According to the range of stack heights commonly observed among racing footwear models (From 20 to 40 mm) (Figure 2), a worthwhile change in running economy and performance could be seen between them due to the consequent change in shoe mass. The results provided by Bertschy et al.¹⁸ and Barrons et al.¹⁷ support this notion, finding a 0.33, 0.34 %, and

0.5% worsened running economy per 10 mm stack height added to the different midsole materials used, resulting, therefore, in 0.7–1.0% per 20 mm. A stack height change of 20 mm is expected to also reach a worthwhile change in running performance, considering the 50 g of differences reported ¹⁷ and its contrasted effect on short efforts ¹⁹. However, its weighted effect on the different long- and mid-distance races, as well as on different athletes' levels, requires further exploration. Likewise, its interaction with the other footwear features that could enhance running performance due to increasing the stack height (e.g., midsole properties ¹⁸, teeter-totter effect" ¹⁴) should be balanced.

4.3 Effect of the midsole properties on running performance and influence of the stack height

The peak midsole deformation, in conjunction with the material stiffness, determines the energy returned ²⁷, which seems to have an effect on the athletes' running economy ^{17,23,24}. Worobets et al. ²⁴ reported that the different properties of the EVA (8 mm peak deformation, 176 N/mm, 69% energy returned) and TPU (10 mm peak deformation, 130 N/mm, 79% energy returned) materials used in the same footwear prototype resulted in a 1% difference on running economy. Using an alternative experimental design that enabled to control the potential influence of the shoe mass, Tung et al. ²³ tested the energetic cost of running barefoot on a standard treadmill surface compared to a cushioned surface made with foam slats of 10- and 20 mm thickness of the Nike Free 3.0 footwear midsole material. Running on the 10 mm surface resulted in a 1.6% lower energetic cost compared with the standard surface, but no significant improvements were observed on the 20 mm one ²³. In this regard, Barrons et al. ¹⁷ observed that reducing the stack height of the four identical footwear prototypes (i.e., 50, 40, 35, and 30 mm) resulted in a decrease in the peak vertical deformation (i.e., from 5 to 3 mm) in conjunction with

an increase in the midsole stiffness (i.e., from 100 to 176 N/mm) which resulted in a similar energy return (i.e., from 86.5 to 83.5%) and running economy.

It was initially proposed that reducing the stack height could bottom out the midsole and, therefore, deteriorate the energy returned and its benefits on running performance ¹². With the example of the force-deformation profile (i.e., 200 N/mm) of the PEBA material used in the Nike footwear models, a midsole of 10 mm thickness would stiffen up before its maximal deformation is reached (i.e., 12 mm) when the mechanical load of an athlete of 68 kg running at 18 km/h is applied (i.e., 2000 N in 185 milliseconds) ¹². Thus, Hoogkamer ¹² stated that considering the stack heights and midsole deformation profiles of current shoe models, the midsole properties would not be affected by the current regulation unless the stack height is reduced further than the maximum deformation capacity of the midsole. In this regard, it is worth noting that, according to the aforementioned results reported by Barrons et al. ¹⁷, reducing the stack height does not seem to alter the energy returned, given that the midsole deformation and stiffness decreased and increased, respectively. However, it should be noted that the midsole deformation and restitution should be synchronized with the mid and propulsive stance phases in order to facilitate the cushioning in conjunction with the vertical and forward propulsion ¹⁴. Therefore, this fact is specific to the running speed to which the midsole properties should be matched.

4.4 Effect of the teeter-totter effect on running performance and influence of the stack height

A reduction in the stack height could alter what has been termed the “teeter-totter” effect ¹⁴. This effect aims to passively enhance the propulsive stance for which different footwear features require to be combined: an increased longitudinal stiffness, typically

reached using a carbon fiber plate, an increased rocker angle (i.e., the upward curvature of the forefoot sole), and a proximal position of the rocker axis (i.e., the starting point of the rocker angle). In this manner, when the ground reaction force travels forward during the end of the stance phase, the rocker axis acts as a fulcrum, and a heel upwards direction force is created during the push-off phase, reducing the muscle force required at the ankle plantar flexors ¹⁴. This mechanism requires a certain midsole thickness in order to reach a sufficient rocker angle to roll by (Figure 3).

It has been suggested that this mechanism improves running performance by 2 to 6% ¹⁴. However, to date, no studies have addressed which rocker axis and angle combination enhances this mechanism. Joubert and Jones ²⁵ have recently compared the effect of different racing footwear models with the aforementioned characteristics on the running economy. To limit the effect of shoe mass, none of the tested shoes differed by more than 30 g. The running economy was improved by 0 to 3%, which indicates that the different shoe constructions could determine the benefits reported.

The rocker angle needed to create this effect could be limited in track spikes where the major stack height limitation has been established (i.e., 20 mm). However, the track spikes construction has been modified accordingly, and this teeter-totter effect has been implemented through the increase in the toe spring angle (i.e., the upward curvature of the forefoot insole), adopting a similar angle to the one established at the rocker (Figure 4), or by approximating the rocker axis (Figure 3). It is worth mentioning that this construction could passively dorsiflex the metatarsophalangeal joint, inhibiting the negative work that the dorsiflexion involves during the push-off phase ^{30,31} and activating the windlass mechanism (i.e., an increased tightness of the plantar aponeurosis) which could also contribute to enhancing running performance ^{31,32}.

5. Conclusions

Reducing the stack height could modify the different footwear features and, therefore, the running performance. With regard to shoe mass, a worthwhile change in running economy and performance could be seen when altering 20 mm the stack height. With respect to the midsole properties, it seems that reducing the stack height does not alter the energy returned, given that the lower midsole deformation is counteracted by an increased stiffness. However, it should be noted that this might affect the timing of the midsole deformation and restitution, which should be matched with the mid and propulsive stance phases. Lastly, the curved geometry of the forefoot sole needed to create the teeter-totter effect could be affected by the stack height reduction. However, current racing footwear designs have counteracted this modification by proximately placing the rocker axis and increasing the toe spring.

6. Future directions

In 2015, Fuller et al. [33] determined after performing a systematic review of the effect of footwear on running performance and running economy that the former had not been investigated yet. In 2022, although a growing interest emerged, Ruiz-Alias et al. [34] highlighted that the lack of studies was still present. Although different limitations are inherent to performance measures (e.g., athlete involvement) [35], meaningful changes in performance derived from footwear can be discerned through the appropriate methodology and statistical analysis. Likewise, performance measures would enable testing footwear in an actual context (i.e., racing pace, fatigue evolution) compared to the running economy requirements seen to date, where running paces are limited to intensities under the lactate threshold or first ventilatory threshold and running times avoid any onset of fatigue [36]. This is of particular interest given that the different footwear features are

expected to significantly change their effects according to the running pace established. Therefore, future studies should consider testing the effect of footwear on running performance through its direct measurement in the competitive context faced by athletes. This should also be extended to sprint and jump events, where the discussed footwear features could also influence performance [37,38]. Likewise, to clearly attribute any performance change to a certain footwear feature, any potential confounders with respect to the footwear design should be controlled, as well as clearly define its specifications (i.e., shoe mass, midsole properties, forefoot geometry).

Lastly, the individual response to this type of footwear trend should also be mentioned. Knopp et al. [39] have recently determined that either Kenyan world-class or European amateur-male runners present a wide response to this type of racing footwear compared to a traditional racing flat with no stiff elements. Specifically, the Kenyan cohort displayed an 11.3% drawback to an 11.4% benefit, and the European cohort displayed a 1.1% drawback to a 9.7% benefit. A potential theory that could explain this variability is the so-called “footwear comfort filter” [40]. Nigg et al. [40] proposed that athletes tend to maintain a certain movement path as this is the most efficient way that the neuromuscular system has to develop it. Accordingly, if an external factor such as running footwear interferes with this preferred path, muscle activity will be increased to preserve this pattern, and therefore, the running economy will be altered. Related to this paradigm, Madden et al. [41] specified that those non-responders to this kind of footwear with an increased longitudinal stiffness maintained their ankle angular velocity, resulting probably in increased muscle activity. Therefore, while there is a common pattern to this new trend in running shoes (i.e., increased longitudinal stiffness, increased rocker angles, and toe springs), the individual nature response should be explored.

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Table 1. Maximum stack height established by the World Athletics from 2019 to 2024 for the different running events.

Event	2019–2022	2022–2024	2024
<800 m	20 mm	20 mm	20 mm
≥800 m	25 mm	25 mm	20 mm
Road	40 mm	40 mm	40 mm
Cross	25 mm spike shoe or	20 mm spike shoe or	20 mm spike shoe or
Country	non-spike shoe	40 mm non-spike shoe	40 mm non-spike shoe

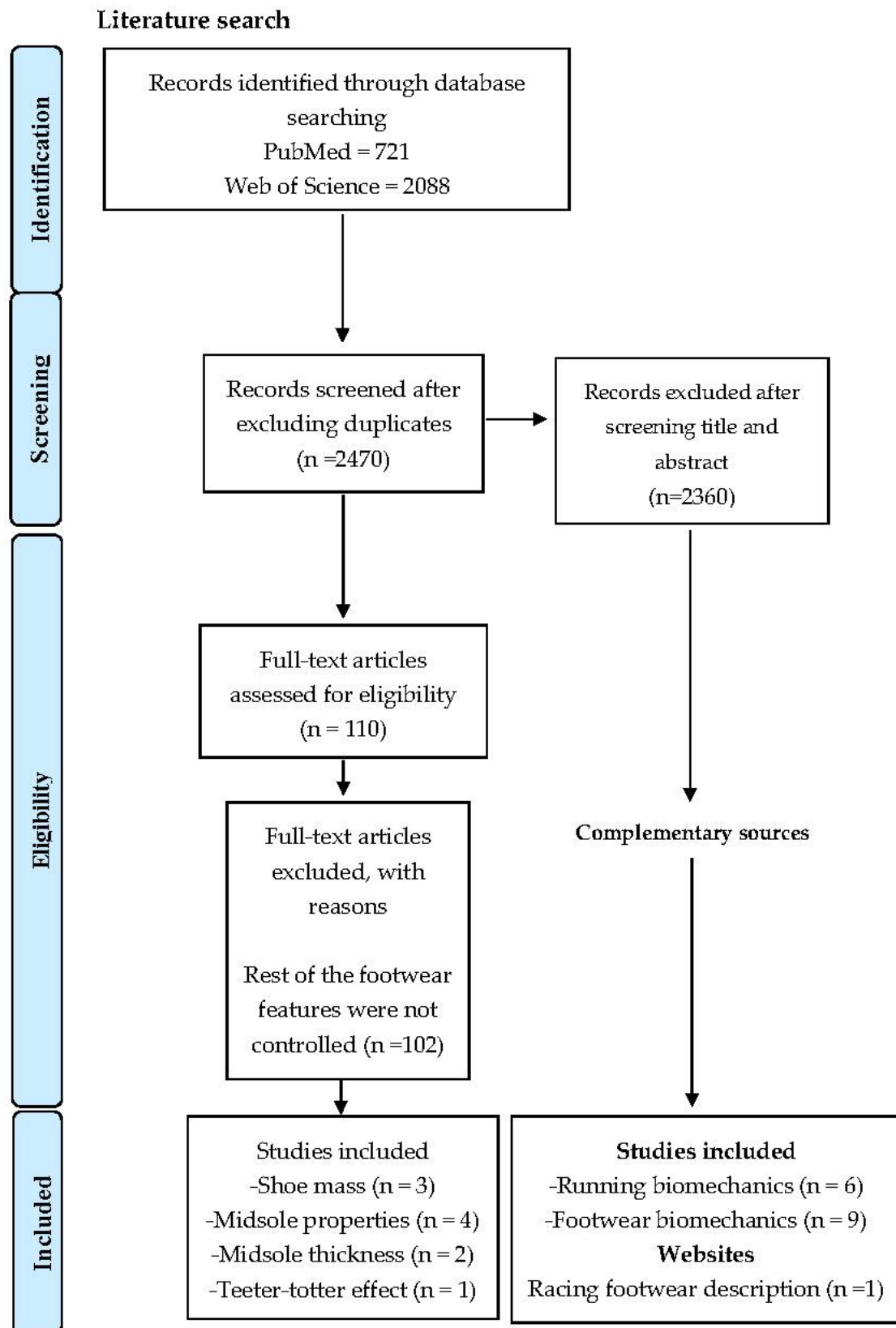


Figure 1. Flow diagram of study selection.

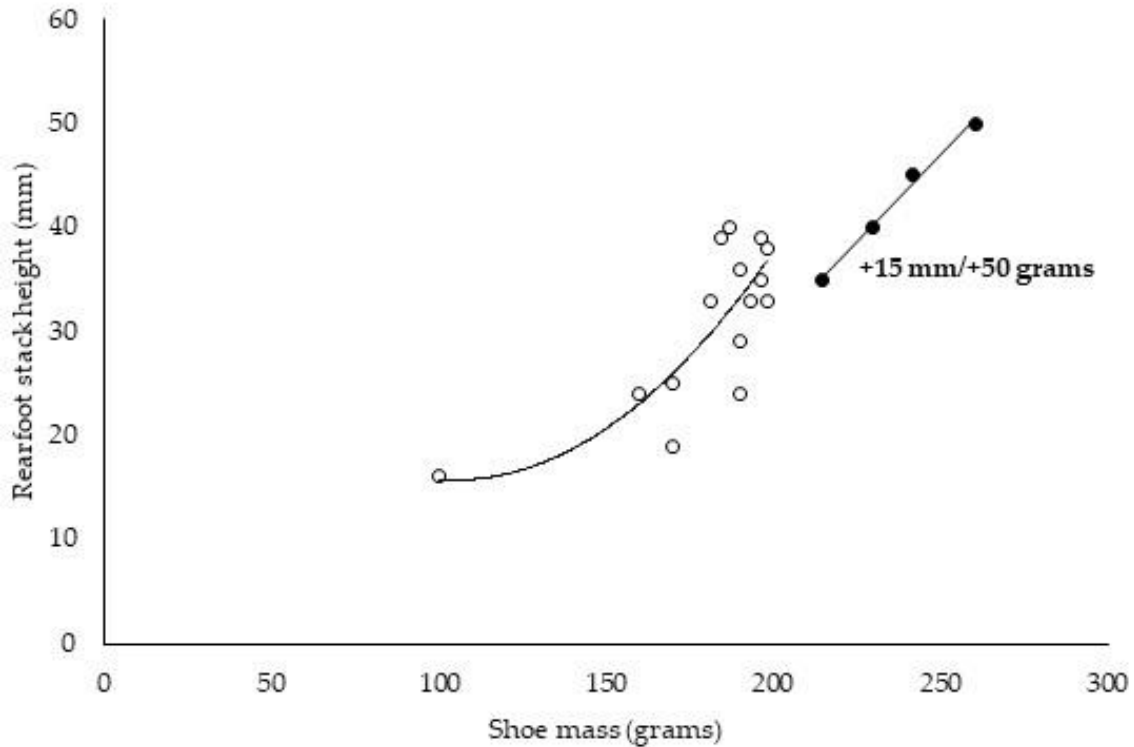


Figure 2. Rearfoot stack height and shoe mass relationship of the same footwear prototype [17] (Black dots: 35 mm, 214.5 g; 40 mm, 229.5 g; 45 mm, 241.5 g; 50 mm, 260.5 g) and from different racing footwear models retrieved from a specialized running footwear website [22]. White dots: Reebok Floatride Run Fast Pro (100 g, 16 mm), Nike Flyknit Racer (160 g, 24 mm), Saucony Fastwitch 9 (170 g, 19 mm), Adidas Adizero Takumi Sen 7 (170 g, 24 mm), Adidas Adizero Takumi Sen 9 (181 g, 33 mm), Nike Zoom Vaporfly 4% (184 g, 39 mm), Nike ZoomX Vaporfly Next% (187 g, 40 mm), PUMA Deviate Nitro Elite (190 g, 36 mm), ASICS Me-taRacer (190 g, 24 mm), ASICS Metaspeed Edge (190 g, 29 mm), Adidas Adizero Takumi Sen 8 (193 g, 33 mm), Saucony Endorphin Pro+ (196 g, 35 mm), Nike ZoomX Vaporfly NEXT% 2 (196 g, 39 mm), ASICS Metaspeed Sky (198 g, 33 mm) and PUMA Fast FWD Nitro Elite (198 g, 38 mm).



Figure 3. Rocker axis position (i.e., the starting point of the forefoot upward curvature) and rocker radius of current footwear models of different brands with different stack heights. The measures were performed with the Kinovea free-access software using a sagittal image of each model placed in the same position. The rocker axis was placed at the center of the rocker radius circle and calculated by the relative position to the total length (i.e., 28 cm for all models). The rocker radius indicates the degree of the upward forefoot curvature of the sole (i.e., a greater rocker radius indicates a lower upward curvature). (TOP): Adidas Adizero Prime X Strung (50 mm, 67%, 10.6 cm), (MIDDLE): Adidas Adizero Pro 3.0 (40 mm, 67%, 11.8 cm), (BOTTOM): Adidas Adizero Takumi Sen 9 (33 mm, 63.8%, 15.9 cm), (TOP): Asics Metaspeed Sky+ (39 mm, 65.8%, 11.2 cm), (MIDDLE): Asics Metaspeed Edge+ (39 mm, 64.7%, 12.8 cm), (BOTTOM): Asics Metaracer Tokyo (24 mm, 57%, 18.2 cm), (TOP): Nike Air Zoom Alphafly Next% (39 mm, 71.1%, 10.5 cm), (MIDDLE): Nike ZoomX Vaporfly Next% 3 (40 mm, 66.4%, 11.7 cm), (BOTTOM): Nike ZoomX Vaporfly NEXT% 2 (39 mm, 66.4%, 13.0 cm). Note that the rocker radius is an approximation.



Figure 4. Toe spring (left) and rocker radius (right) values, as well as rocker axis position of current track spikes of different brands for long, mid, and sprint events. (TOP): Adidas Adizero Avanti TYO (18.6 cm, 18.6 cm, 61.8%), (MIDDLE): Adidas Adizero Ambition (15.9 cm, 14.1 cm, 64%), (BOT-TOM): Adidas Adizero Finesse (17.9 cm, 17.9 cm, 59.3%), (TOP): Nike ZoomX Dragonfly (19.4 cm, 19.4 cm, 54.4%), (MIDDLE): Nike Air Zoom Victory (18.9 cm, 18.9 cm, 62.3%), (BOTTOM): Nike Air Zoom MaxFly (16.7 cm, 15.5 cm, 59.3%). Note that the rocker and toe springs radius are an approximation.

**Artículo 3: Estudio experimental sobre el efecto del
calzado legal e ilegal en el rendimiento y la
biomecánica de carrera en pista**

Influence of the World Athletics Stack Height Regulation on Track Running Performance

Running head: The Effect of Footwear on Track Running Performance

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Abstract

A new footwear regulation based on limiting the stack height (i.e., amount of material between the feet and the ground) has been established by World Athletics in order to ensure that performance is achieved through the primacy of human effort over technology in running shoes. The effect of legal and illegal shoes on running performance is therefore needed to determine its effectiveness. Thus, this study aimed (i) to compare the effect of two footwear models categorized as legal and illegal by the World Athletics regulation on track running performance, and (ii) to analyze the derived metrics of the athletes' biomechanics when using each footwear model at racing paces. Within one week, 14 highly trained athletes performed two testing sessions composed of two-time trials of 9- and 3-minutes duration with 30 minutes recovery between them. The athletes wore the "Nike ZoomX Dragonfly" track spikes model and the "Nike ZoomX Vaporfly Next % 2" marathon shoe model in a counterbalanced randomized order. The results revealed that (i) there was only a small worthwhile improvement in the 3 minutes time trial when using the marathon shoes of 0.97 % (-0.04 to 1.98 %), and (ii) there was a main effect of footwear in 7 out of the 9 biomechanical variables analyzed ($p \leq 0.050$). The ground contact time was the unique performance predictor ($p = 0.005$, adjusted $R^2 = 0.476$). Altogether, the use of legal and illegal running shoes altered the runners form which only influenced the mid-distance performance.

Keywords: Endurance performance, running biomechanics, doping technology.

1. Introduction

Recent advances in footwear technologies have marked a turning point in the running field due to their effect on the running economy (RE) ¹. Reducing the shoe weight, increasing the longitudinal stiffness, raising the rocker angle (i.e., the angle between the ground and the line connecting the shoe distal and the apex), or enhancing the midsole properties have been the footwear feature modifications pursued for such effects ².

The improved RE has been remarkable in long-distance performances which led World Athletics (WA) to take action on this issue ³. A new footwear regulation was established in order to ensure that running performance was achieved through the primacy of human effort over technology in running shoes ⁴. From the different footwear features, the regulation was based on limiting the stack height and this was applied for the different running events (i.e., < 800 meters: 20 mm; ≥ 800m: 25 mm; Road: 40 mm; Cross-country: 20 mm spike shoe or 40 mm non-spike shoe). Burns and Tam ⁵ suggested that this could be a way of limiting the rest of the features that enhance RE. However, several authors have opposed to this proposal. Frederick ⁶ objected to this point due to a lack of evidence and consensus on the measurement of the stack height. Hoogkamer ⁷ argued that increasing the midsole thickness results in no advantage for RE due to the increase in weight and instability. Hoogkamer ⁷ also added that the midsole properties of current midsole materials are not compromised by such limitations since the greatest deformations were found to be in 12 millimeters ¹, needing just a few more millimeters to avoid any deterioration of the resilience and compliance properties. Nigg and colleagues ⁸ subsequently contributed to this debate by discussing the potential magnitude of each shoe feature on RE. The authors mentioned that the major effect comes from the curved carbon fiber plate that generates the so-called “teeter-totter effect” ⁹.

To the authors' knowledge, no studies have analyzed the effectiveness of this regulation by comparing the effect of using legal and illegal shoes on running performance. In particular, a great interest resides in running track events where the major stack height limitation has been established (i.e., ≤ 20 mm) (5). This regulation limits the use of the so-called "marathon racing shoes", built with a midsole stack height close to 40 mm by the different brands ¹⁰ which have shown to improve RE compared to long-distance track spikes ¹¹.

The existing literature has been focused on comparing the footwear effect on RE, a surrogate measure of long-distance running performance, which requires running at submaximal velocities (i.e., $<$ ventilatory/lactate threshold) ¹². However, it is well known that runners adopt different biomechanical patterns at higher running velocities which can vary the behavior of the different footwear features ^{13,14}. In this regard, a difference in shoe weight will have a greater impact at high running velocities where the internal work (i.e., the work done to accelerate the body segments regarding the center of mass) takes a prominent role ^{13,14}. On the other hand, the benefits reported by current midsole materials might be also conditioned to their force-deformation profiles and the maximum vertical ground reaction force that the athletes exert at a given stance time. This would condition the magnitude of the energy returned, its location, and timing ^{14,15}.

It is also well noted that the benefit that RE has on running track events is controversial and might be dependent on the race distance ^{16,17}. Whereas the RE has not been considered a determinant factor at 800 and 1500 meters ^{16,18}, in 3000 meters has been shown to be strongly linked ¹⁷. This controversy might rely on the inability to capture the anaerobic metabolic contribution through standard RE measurements ¹⁹. However, irrespectively of the energy source, an enhanced mechanical efficiency caused by footwear would be derived in an improved running performance. Thus, based on the

aforementioned, this study aims (i) to compare the effect of two footwear models categorized as legal and illegal by the WA regulation on track running performance, and (ii) to analyze the derived metrics of the athletes' biomechanics when using each footwear model at racing paces.

2. Methods

2.1 Experimental approach to the problem

In a counter-balanced randomized order, athletes were tested on separate occasions with each footwear model. After a standardized warm-up, athletes completed two-time trials of 9-and 3-minutes with 30 minutes of recovery between them. Within one week, the same session was repeated with the corresponding footwear model. Of note, athletes were encouraged to refrain from vigorous activity in the 48 hours prior to each testing session. Both testing sessions were performed on an outdoor track under similar environmental conditions ($\sim 22^{\circ}\text{C}$ and $\sim 40\%$ humidity, wind $< 10\text{ km/h}$) and time of day ($\pm 1\text{ hour}$).

2.2 Subjects

A group of 14 highly trained athletes (age: 27 ± 9 years, height: $178 \pm 4\text{ cm}$, body mass: $69 \pm 6\text{ kg}$; 3000 meters season best: $09:08 \pm 00:22\text{ min:sec}$; Equivalents WA score²⁰: 685 ± 100 points; training volume: 60 ± 20 kilometers per week) participated in the study. The following inclusion criteria were established to select highly trained athletes²¹: (i) to perform a training volume of > 150 minutes per week, and (ii) to compete nationally. Athletes were used to running with both footwear models as part of their training programs and competitions. All subjects were informed about the research purpose and procedures of the study before signing a written informed consent form. The

study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the institutional review board (No. 2276/CEIH/2021).

2.3 Footwear conditions

Two footwear models considered legal (i.e., ≤ 20 mm) and illegal (> 20 mm) by the WA regulation for track events were used. The legal footwear model used was the “Nike ZoomX Dragonfly” track spikes of 20 mm stack height. The illegal footwear model used was the “Nike ZoomX Vaporfly Next % 2” marathon racing shoes of 40 mm stack height. Both models were owned by athletes with the premise of not exceeding 50 kilometers of use. If not, a new pair of shoes were provided. In those cases, a familiarization period was done prior to the testing session. The footwear details are indicated in figure 1.

-Figure 1 about here-

2.4 Track testing sessions

Both testing sessions were performed on the outdoor track of the University of Granada Sports Science Faculty. The track lap was 322 meters of distance. The athletes begin the testing sessions with a standardized warm-up which consists of 10 minutes at low-to-moderate intensity (i.e., intensity corresponding to easy long-running sessions). After a series of dynamic mobility exercises, 2-3 progressive high-intensity runs of 100 meters were done to complete the warm-up. Then, athletes performed individually two-time trials of 9- and 3-minutes with 30 minutes of recovery. One researcher was close to the athletes’ finish positions so once completed each trial, a mark of the last foot entered on time was established to subsequently measure the distance completed. A wheel odometer was used to measure the distance completed. The Borg CR100 scale reported immediately after the testing session was used to determine the perceived effort.

2.4 Running biomechanics

The running power meter (Stryd Summit Power Meter, Boulder, CO, USA) was used to determine the following biomechanical variables: (i) running effectiveness (REF): Meters per second achieved by each watt per kilogram, (ii) form power (FP): The component of power of the vertical bouncing of the center of mass, (iii) step frequency (SF): Number of steps per minute, (iv) step time (ST): The time from the beginning of the step cycle (take-off) to the end (previous frame to take-off), (v) stride length (SL): Distance covered in a stride cycle, (vi) ground contact time (GCT): The time from when the foot contacts the ground to when the toes lift off, (vii) duty factor (DF): Fraction between contact time and step time, (viii) leg spring stiffness (LSS): Change in vertical leg length in response to the maximum vertical force of a step, and (ix) vertical oscillation (VO): Vertical movement of a runner's center of mass between steps. This device has been shown to report the aforementioned variables validly and reliably ^{22,23}. This one was placed on the laces of the right footwear on each testing session. Records were synchronized from the pod to the Stryd platform (<https://www.stryd.com/powercenter>) and then exported to an Excel spreadsheet (Microsoft, Redmond, USA) for subsequent analyses.

2.5 Footwear comfort

Footwear comfort was assessed through a 100 mm visual analogue scale with the ends labelled as “not comfortable at all” and “most comfortable condition imaginable” after each testing session ²⁴. Athletes also rated their usual footwear after completing the warm-up in both testing sessions to test their reliability. Those athletes with an ICC < 0.500 were discarded ²⁵.

2.6 Statistical analysis

Descriptive statistics are represented as mean $\pm$ standard deviation (SD). The normal distribution of data and homogeneity of variances were confirmed through the Shapiro-Wilk test and Levene's tests, respectively. A two-way repeated measures analysis of variances (ANOVA) ([spikes vs. marathon] $\times$ [9 vs. 3]) with Bonferroni post hoc test was applied to compare running performance and biomechanical variables. A paired-samples t-test was used to compare the perceived comfort and effort in the two footwear conditions. Standardized effects were calculated as the within-subjects mean difference divided by the SD ²⁶. The following scale was used to interpret the magnitude of the effect: trivial (< 0.20), small ($0.20-0.59$), moderate ($0.60-1.19$), large ($1.20-2.00$), and extremely large (> 2.00) ²⁷. The smallest worthwhile changes (SWC) of each variable were set at 0.2 times the within-subjects differences SD ^{28,29}. A stepwise multiple regression analysis was performed to determine any potential relationship between changes in the running performance and the biomechanical variables. Statistical significance was accepted at $p < 0.05$ level. Data analysis was performed using the software package SPSS (IBM SPSS version 25.0, SPSS Inc., Chicago, IL., USA).

3. Results

3.1 Running performance

No significant main effect was observed for footwear on running performance ($F_{(1, 13)} = 0.41$, $p = 0.535$) (Table 1). In addition, although their interaction also did not reach statistical significance ($F_{(1, 13)} = 2.70$, $p = 0.124$), the marathon shoes revealed a *small* improvement in the 3 minutes time trial of 0.97 % (95% CI: -0.04 to 1.98 %) that was over the SWC (0.35 %) (Figure 2). A *maximal* perceived effort was reached in both testing sessions trials (Track spikes: 99 [13]; Marathon shoes: 99 [15]; $p = 0.900$). With respect

their 3000 meters season best, athletes completed the 9 minutes at running pace +2.8 (2.6) % and 3.1 (2.6) % and the 3 minutes at -4.1 (3.0) % and -5.4 (3.9) % with the track spikes and marathon shoes, respectively.

-Table 1 about here-

-Figure 2 about here-

3.2 Running biomechanics

Eight out of 9 biomechanical variables revealed a significant main effect for time trial ($F_{(1, 13)} \geq 12.90$, $p \leq 0.004$) except for the DF ($F_{(1, 13)} = 2.66$, $p = 0.134$) (Table 1). A significant main effect for footwear was also obtained in 7 out of 9 biomechanical variables ($F_{(1, 13)} \geq 4.96$, $p \leq 0.050$), except for the REF and GCT ($F_{(1, 13)} \leq 3.60$, $p \geq 0.082$), although these ones were over the SWC except for the last in the 9 minutes time trial. No significant interactions were reported for any biomechanical variable ($F_{(1, 13)} \leq 4.33$, $p \geq 0.064$). Figure 3 provides the percentage of change observed for each biomechanical variable during the 9- and 3- minutes time trial. The stepwise multiple linear regression analysis revealed that the changes in GCT was the unique performance change predictor ($F_{(1, 13)} = 11.88$, $p = 0.005$, adjusted R^2 : 0.476) in the 3 minutes time trial. The resulted regression equation was (Δ 3 minute distance = $-3337 \cdot \Delta$ GCT + 5.14).

-Figure 3 about here-

3.3 Footwear comfort

No significant differences were observed between footwear models ($p = 0.168$), although the mean change revealed a *small* increased perceived comfort in the marathon shoes (ES: 0.37 [95% CI: -0.81 to 4.27]) that was over the SWC (ES: 0.20) (Table 1).

4. Discussion

This study was designed to compare the effect of two footwear models categorized as legal and illegal by the WA regulation on track running performance, and to analyze the derived metrics of the athletes' biomechanics when using each footwear model at racing paces. The results of the present study revealed that there was no main effect of footwear on running performance. However, athletes showed a *small* improvement when using the marathon shoes in the 3 minutes time trial of 0.97 % (-0.04 to 1.98 %) which was over the SWC (0.35 %). In addition, there was a main effect of footwear in 7 out of 9 biomechanical variables analyzed during the 9- and 3-minutes time trial, which are summarized in a reduced DF and an increased LSS and VO when using the marathon shoes. Finally, the GCT was the unique performance predictor parameter in the 3 minutes time trial explaining 47.6 % of the variance.

The effect of footwear on running performance has been commonly analyzed through the measurement of RE at submaximal velocities, leaving aside its direct measurement. In 2015, Fuller and colleagues³⁰ conducted a systematic review of the effect of footwear on running performance and RE, finding no studies related to the former. Healey and colleagues¹⁹ discussed the potential reasons for this knowledge gap. At racing paces, calculating the rate of metabolic energy expenditure from oxygen uptake and carbon dioxide production rates is not valid as the anaerobic metabolic pathways' contributions are ignored¹⁹. Thus, RE measurements are performed at submaximal velocities avoiding any onset of fatigue which might result in different footwear effects than in a racing context. Different studies have shown how a firstly improved RE under a certain footwear did not lead to an improvement in running performance³¹⁻³³. Differences in running performance have been also reported despite similar RE measures between footwear models²⁸. This might be influenced by the distances tested and the

muscle fatigue evolutions when using different footwear categories (e.g., minimal vs. maximal shoes)^{32,33}. Thus, in the present study, the effectiveness of the WA regulation has been tested through direct measurement of running performance under field conditions in time trials of different durations.

Considering the isolated effect on running performance, diverse footwear comparisons have been made. Fuller and colleagues³¹ compared the effect of using the Asics Gel Cumulus-14 conventional shoe model and the Asics Piranha SP4 minimal shoe model on 5000 meters performance, finding a ~2 % improvement when using the minimal shoes (~20:44, -22 seconds). On the other hand, Dinato and colleagues³³ found no differences in 3000 meters running performance (~11:41) between the Adidas Energy Boost marathon shoe model and the Nike Free Run 2 minimal shoe model. The unique comparison of the marathon shoe model used in the present study on running performance was reported by Hébert-Losier and colleagues²⁸, who compared the effect of using the first Nike Vapofly 4 % marathon shoe model version and the Saucony Endorphin racing flats in 3000 meters performance, finding a ~1.8 % improvement when using the marathon shoes (~11:07, -13 seconds). It is well noted that the aforementioned comparisons are related to footwear models used in road and not in track competitions. In addition, the recreational level of the athletes recruited limits the extrapolation of such improvements into high-caliber athletes where these ones become more relevant. To the authors' knowledge, no comparisons have been made in running performance between track spikes and road shoes. The only data reported comes from Barnes and Kilding¹¹ who mentioned that the high-caliber athletes recruited for comparing the effect of using the Nike Zoom Matumbo track spikes model and the Nike Vaporfly 4 % marathon shoe model on RE, competed in 3000 and 5000 meters with this last model and their own track spikes, finding a ~1.9 % improvement with the marathon shoes considered today illegal.

However, these results should be interpreted with caution considering the non-counterbalanced order used and the potential confounding effects of training as well as the diverse track spikes used. Within a one-week period, our sample of athletes completed the testing sessions with each footwear in a randomized counterbalanced order, finding only a worthwhile improvement (i.e., $> 0.35\%$) in the last time trial of 0.97% (-0.04 to 1.98%). Such improvements in running performance represent the differences between the 4 first places in the last 3000 meters ($\sim 0.35\%$) and 1500 meters ($\sim 0.60\%$) World Indoor and Olympic finals, or the differences between the previous and recent world mile records ($< 0.63\%$). Therefore, these differences appear to be of significance in the high performance context.

A recent publication has highlighted the lack of a biomechanical explanation for the running performance improvements observed in this new footwear model ³⁴. One of the potential reasons is that running styles are a set of parameters often analysed independently, although running technique is a dynamic system where changes in one parameter are likely to affect another ³⁵. As indicated in table 1, there was a main effect of footwear in 7 out of 9 biomechanical variables analyzed during the 9- and 3-minutes time trial. Gindre and colleagues ³⁶ differentiate two major running patterns, the aerial and terrestrial which can be associated to the ones created by the marathon shoes and track spikes, respectively. Athletes with an aerial pattern are characterized by longer FT and greater VO, maximum vertical force (i.e., FP), and LSS than the terrestrial ones ³⁶. On the other hand, athletes with a terrestrial pattern are characterized by longer GCT and lower LSS. Both running patterns can reduce the metabolic demands through the enhanced passive elements contribution or the reduced external work by the decrease of the vertical displacement, which might explain the non-significant differences obtained in the 9 minutes time trial ³⁶.

On the other hand, the mechanical demands of mid-distance events appear to be more concise being the plantar flexors work as the main limiting factor ³⁷. Willer and colleagues ³⁷ showed that at a constant mid-distance pace (i.e., time to exhaustion ~ 3 minutes), the plantar flexors' positive work was significantly reduced from the start of the run producing a compensatory redistribution to the knee and hip positive works in a group of competitive mid-distance runners. Such plantar flexors limitation seems to reside in the greater relative contribution to the overall positive work performed during the stance phase, reaching a ~ 70 % of the total compared to the knee (~ 14 %) and hip (~ 16 %) contributions during the unfatigued state ³⁷. The decreased GCT in conjunction with the increased SL and VO observed with the marathon shoes indicates that the ankle plantar flexor action was optimized. The plantar flexion mechanism has been the main focus of recent technological advances through the inclusion of the carbon fibre plate with a curved geometry that generates the so-called “teeter-totter effect” ⁹. When ground reaction force travels forward during the end of the stance phase, the rocker axis of the footwear acts as a fulcrum and a heel upwards direction force is created during the push-off phase ⁹. In this way, this first-class lever transforms the vertical kinetic energy into rotational kinetic energy enhancing thus the stance propulsive phase. This mechanism requires the curved geometry of the plate, which might be reduced by the current stack height limitation ⁹.

As Burns and Tam ⁵ suggested, limiting the stack height might be a measure that limits the footwear features that are contributing to enhancing running performance. In addition to the aforementioned limitation of the teeter-totter effect, other footwear features such as the midsole properties might be also altered. The midsole material of the shoe models used in the present study has been shown to deform 12 mm for a peak force of 2000 N applied during 185 ms, corresponding to a force-time simulation of an athlete

of 65 kg running at 18 km/h¹. During the midsole deformation, the mechanical work is stored to then being restored with a certain percentage of loss (~ 13 % in the midsole material of the shoe models used)¹. To enhance running performance, in addition to the returned magnitude, the stored and restored mechanical work of the midsole must be timed to the mid and propulsive stance phases¹⁵. Minimal shoe models with a reduced stack height have shown an incorrect timing compared to the current advanced shoe models in addition to the different magnitudes¹⁵. Despite the footwear's mechanical properties not being measured in the present study, athletes did not perceive any difference in comfort between the track spikes and the marathon shoe models of 20 and 40 mm stack heights, respectively.

Based on the results obtained in the present study, the WA stack height regulation limits running performance in function of the running intensity. However, few limitations need to be highlighted in order to correctly interpreted the results obtained. The 3 minutes time trial was susceptible to being influenced by the 9 minutes time trial. However, it has been established that the 30 minutes recovery period is enough to not influence performance in the rest of the time trials performed within the same testing session^{38,39}. Likewise, these results should be only extrapolated to the level of athletes recruited. Further research is also needed to consolidate these results on longer (i.e., 5000 and 10.000 meters) and shorter (i.e., ≤ 400 meters) track events as well as on different athletes' performance levels. It is also worth noting that the different brands have adapted their different models to the current regulation maintaining the different footwear features that have shown to improve RE¹⁹. Thus, further comparisons between previous and actual legal track spikes models are also required to understand the scope of this revolution in running shoes.

In conclusion, the use of the illegal marathon shoe model resulted in a worthwhile improvement of 0.97 % (-0.04 to 1.98 %) in the 3 minutes time trial which was mainly explained by a reduced GCT. In the 9 minutes time trial, the aerial and terrestrial patterns acquired with the marathon shoes and the track spikes models respectively did not result in any performance differences.

5. Practical applications

Athletes and practitioners should be aware of the effects of current footwear regulations on their performance or running biomechanics. The use of the illegal model induces an aerial pattern (i.e., longer flight times, greater vertical oscillation) which implies potential improvements in the mid-distance running performance. However, no changes in the long-distance performance are appreciable between the terrestrial (i.e., greater step frequency, lower leg stiffness) and aerial patterns acquired with the legal (track spikes) and illegal (marathon shoes) models.

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Figure 1. The Nike ZoomX Dragonfly track spikes and the Nike ZoomX Vaporfly Next % 2 marathon shoes. In 9 US (27.5 centimeters) size, a difference of 57.30 grams was found (Track spikes: 138.90 grams; Marathon racing shoes: 196.19 grams) using a precise digital scale. Both models present the same midsole material (i.e., ZoomX) and a full-length embedded curved plate. The track spikes model has 6 cleats of 3 millimeters positioned on the forefoot region. The stack heights (in millimeters) and apex position (percentage of the total length) measured with the free-access software “Kinovea” are present.

Table 1. Running performance, spatiotemporal parameters and perceived comfort reported at the 9- and 3-minutes all-out efforts using spikes and marathon shoes.

Variable	Time trial	Track spikes	Marathon shoes	ES (95 % CI)	SWC	Δ (95 % CI)	Footwear effect (p)	Time trial effect (p)	Interaction effect (p)
Distance (meters)	9 minutes	2849 (102)	2846 (105)	0.14 (-0.41 to 0.69)	6.45	4.40 (-12.89 to 21.69)	0.535	<0.001	0.124
	3 minutes	1038 (36)	1049 (44)	-0.57 (-1.15 to 0.00)	3.73	-10.64 (-21.40 to 0.12)			
Running effectiveness (m.s/W.kg)	9 minutes	1.00 (0.04)	1.02 (0.03)	-0.34 (-0.92 to 0.23)	0.007	-0.01 (-0.03 to 0.01)	0.257	<0.001	0.639
	3 minutes	1.03 (0.04)	1.04 (0.03)	-0.42 (-1.07 to 0.23)	0.006	-0.01 (-0.03 to 0.01)			
Form power (W/kg)	9 minutes	1.10 (0.06)	1.12 (0.06)	-1.06 (-1.65 to -0.49)	0.003	-0.02 (-0.03 to -0.01)	<0.001	<0.001	0.305
	3 minutes	1.05 (0.06)	1.07 (0.06)	-1.67 (-2.30 to -1.03)	0.002	-0.02 (-0.03 to -0.01)			
Step frequency (spm)	9 minutes	183 (7)	181 (8)	0.47 (-0.23 to 1.19)	0.67	1.6 (-0.8 to 4.0)	0.013	<0.001	0.876
	3 minutes	193 (9)	191 (9)	0.94 (0.27 to 1.61)	0.40	1.9 (0.5 to 3.2)			
Stride length (meters)	9 minutes	3.50 (0.15)	3.53 (0.15)	-0.48 (-1.15 to 0.18)	0.01	-0.03 (-0.08 to 0.01)	0.016	<0.001	0.064
	3 minutes	3.64 (0.15)	3.71 (0.17)	-0.96 (-1.60 to -0.33)	0.01	-0.07 (-0.11 to -0.02)			
Ground contact time (seconds)	9 minutes	0.18 (0.07)	0.18 (0.09)	0.13 (-0.47 to 0.83)	0.001	0.008 (-0.003 to 0.005)	0.082	0.001	0.113
	3 minutes	0.18 (0.07)	0.17 (0.09)	0.92 (0.31 to 1.53)	0.001	0.004 (0.001 to 0.006)			
Step time (seconds)	9 minutes	0.33 (0.01)	0.33 (0.01)	-0.62 (-1.29 to 0.05)	0.00	-0.00 (-0.01 to 0.00)	0.014	<0.001	0.696
	3 minutes	0.31 (0.01)	0.31 (0.01)	-0.88 (-1.57 to -0.23)	0.00	-0.00 (-0.00 to -0.00)			
Duty factor (%)	9 minutes	0.56 (0.02)	0.55 (0.04)	0.22 (-0.45 to 0.89)	0.00	0.01 (-0.01 to 0.03)	0.050	0.134	0.218
	3 minutes	0.57 (0.02)	0.56 (0.02)	1.40 (0.76 to 2.04)	0.00	0.02 (0.01 to 0.02)			
Leg spring stiffness (kN/m)	9 minutes	10.69 (1.03)	11.22 (1.10)	-1.55 (-2.18 to -0.91)	0.07	-0.53 (-0.75 to -0.31)	<0.001	0.004	0.345
	3 minutes	10.36 (1.18)	11.02 (1.13)	-1.29 (-1.92 to -0.65)	0.10	-0.66 (-0.98 to -0.33)			
Vertical oscillation (centimeters)	9 minutes	7.95 (0.77)	8.14 (0.87)	-0.75 (-1.30 to -0.19)	0.06	-0.23 (-0.40 to -0.06)	0.001	<0.001	0.282
	3 minutes	7.18 (0.77)	7.46 (0.81)	-1.27 (-1.87 to -0.67)	0.04	-0.28 (-0.41 to -0.14)			
Comfort (millimeters)	9 and 3 minutes	94.5 (7.57)	96.91 (5.05)	-0.37 (-0.93 to 0.17)	0.92	-1.73 (-4.27 to 0.81)	0.168	--	--

ES: Effect size; SWC: Smallest worthwhile change (0.2*SD); Δ: Mean change; 95 % CI:

95% confidence interval.

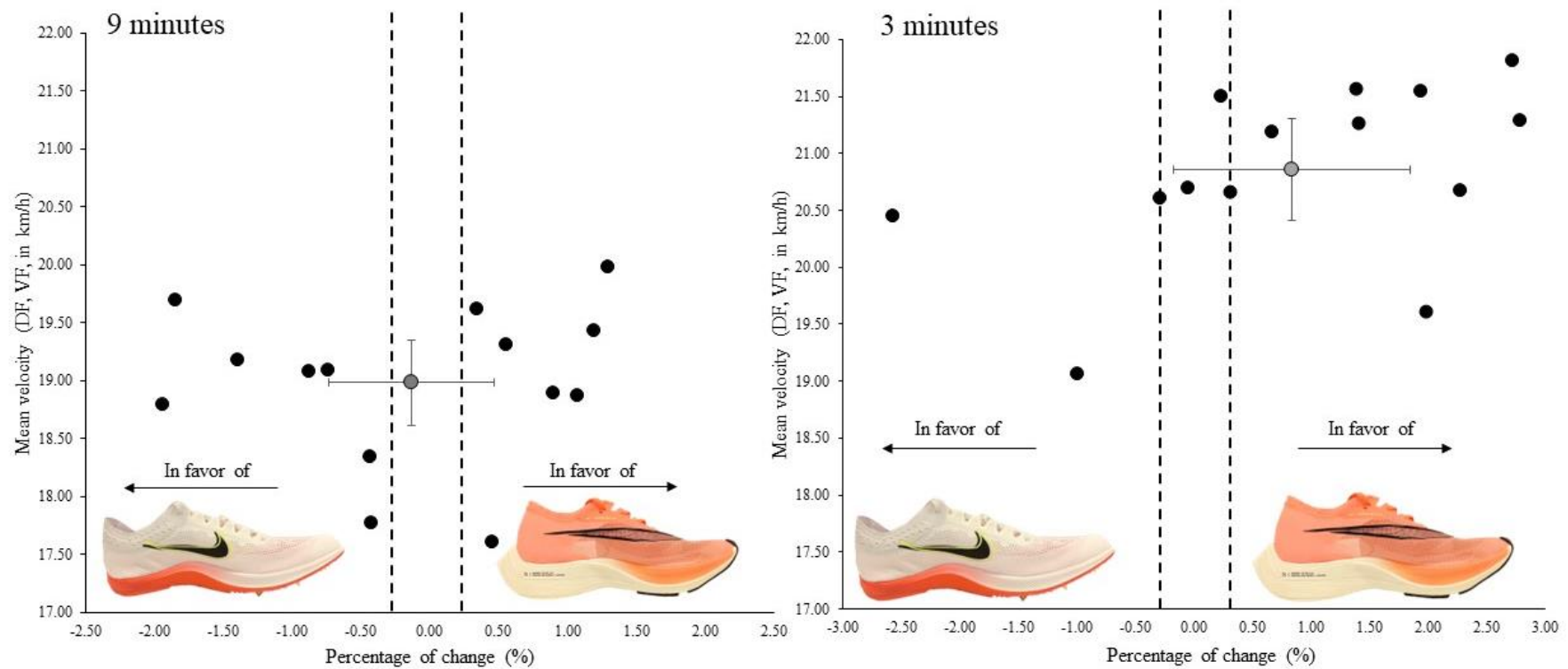


Figure 2. Running performance differences observed in the 9-and 3-minutes time trial between the track spikes (legal) and marathon shoes (illegal) models. Dashed lines represent the smallest worthwhile change ($0.2 \times SD$). DF: Nike ZoomX Dragonfly track spikes; VF: Nike ZoomX Vaporfly Next % 2 marathon shoes.

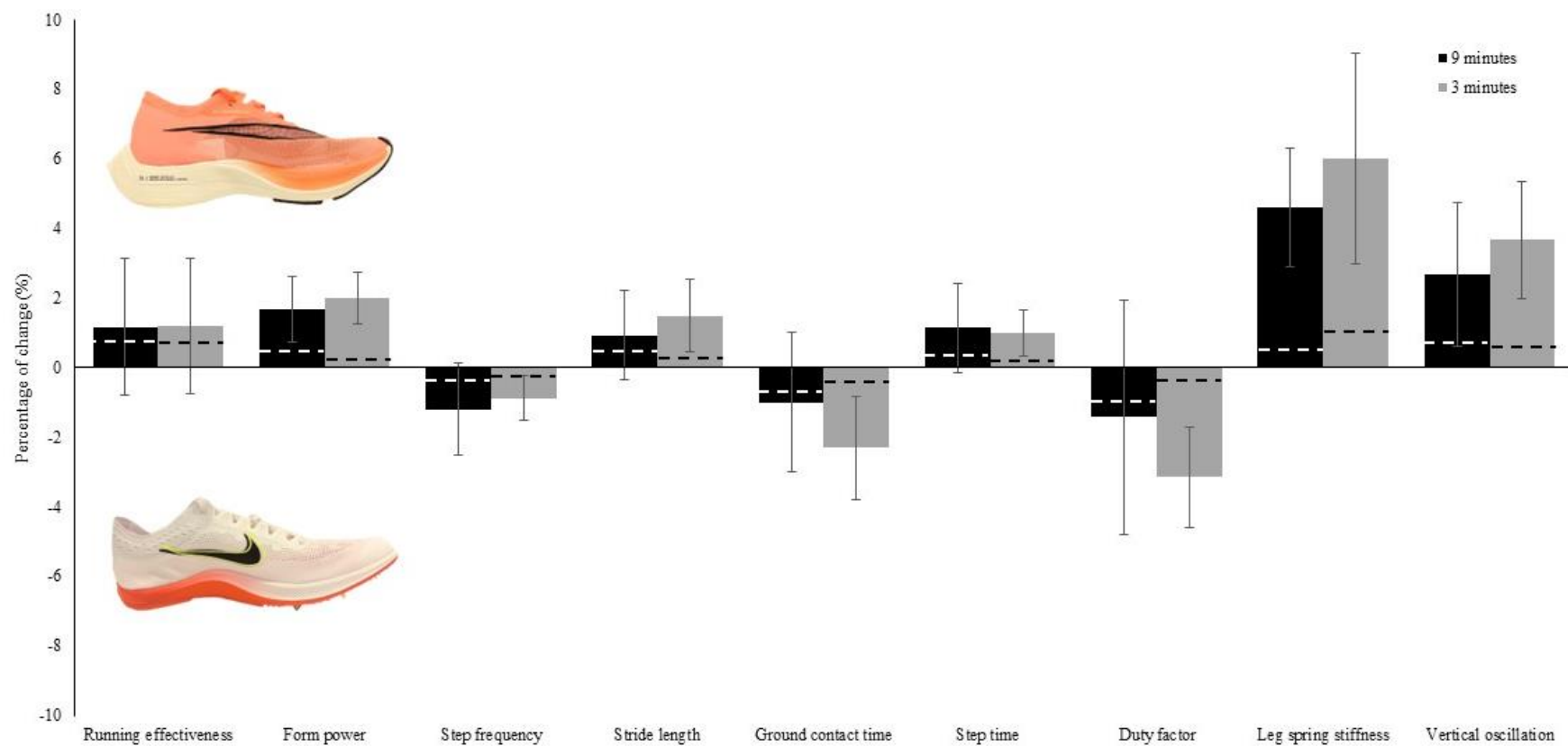


Figure 3. Percentage of change observed in the biomechanical variables analyzed during the 9-and 3-minute time trial when using the legal and illegal shoe models. Dashed lines represent the smallest worthwhile change ($0.2 \times SD$).

**Artículo 4: Estudio experimental sobre el efecto del
calzado de competición en la fatiga neuromuscular**

**The effect of using marathon shoes or track spikes on the neuromuscular fatigue
caused by a long-distance track training session**

Running head: The effect of footwear on neuromuscular fatigue

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Abstract

This study aims to compare the effect of the Nike ZoomX Dragonfly track spikes and the Nike ZoomX Vaporfly Next % 2 marathon shoes on the fatigue manifestations present over and after a long-distance track training session. Thirteen highly trained athletes completed two training sessions (i.e., 9- and 3-minutes time trials with complete recovery) with the aforementioned footwear models. The pace, ground contact time, and stride length were measured over the time trials and maximal countermovement jumps were performed previously and after the training session. The results revealed that, although there was no significant interaction in the pace distribution ($p \geq 0.072$), athletes tend to be only able to increase the pace at the last lap with the marathon shoes (5.4 meters [-3.7 to 14.5 meters]) meanwhile with the track spikes it further decreased (-3.1 meters [-9.8 to 3.6 meters]). A reduced ground contact time over the session ($p = 0.025$) and a tendency toward increasing stride length ($p = 0.09$) in the last time trial were observed. The significant interaction on the countermovement jump height ($p = 0.023$; Track spikes: -5.60 %; Marathon shoes: 0.61 %) also indicates that footwear influences the resulted allostatic load.

Keywords: Running performance, Training, Fatigue.

1. Introduction

Long-distance running performance is mediated by several factors where running economy (RE) among others plays a major role ¹. Different footwear categories (e.g., marathon shoes, minimal shoes) have shown to have a large influence on it, but their effect over the course of a long-distance might fluctuate due to different fatigue evolutions ².

The recent advances in footwear technology have shown how RE can be enhanced by modifying the muscular effort needed for cushioning the impact with the ground due to the enhanced midsole properties ³, or by placing the athletes in a more favorable position on their force-velocity profile through the inclusion of a carbon fiber plate ⁴. The existing evidence of these improvements relies on comparisons among different route models, but little is known about their effects compared to track spikes where these advances have been also implemented and are widely used by athletes in track training or competitions ⁵. It has been determined that athletes improve 2.6 % their RE when using the well-known Nike Vaporfly 4 % marathon shoe compared to the Nike Zoom Matumbo long-distance track spikes ⁶. However, the submaximal velocities (14-18 km/h; < lactate threshold) and the recovery period established between conditions are far away from the paces and fatigue states of a track training or racing contexts. Thus, it is important to note that a firstly improved RE has not been always transferred into running performance ⁷.

Neuromuscular fatigue has been categorized as central or peripheral according to the origin of the failure in the excitation-contraction coupling (i.e., deficit in voluntarily activation, decrease in sarcolemma excitability, cytoskeletal muscle damage) ⁸. Different fatigue manifestations have been reported during and after high-intensity intermittent track training sessions and continuous efforts ^{9,10}. Bachero-Mena and González-Badillo ⁹

described the mechanical and metabolic response of a typical mid-distance track training session (5×200 meters with 4 minutes rest) performed on an outdoor track. Running times progressively increased as a result of an increase in ground contact times (GCT) and a reduced stride length (SL). The resulting fatigue was also appreciable in the reduction of the countermovement jump (CMJ) height performed between bouts which was inversely related to blood lactate concentrations⁹. Likewise, Nummela et al.¹⁰ found a reduction in the lower limbs electromyography muscle activity during the pre-activation phase of a 5-km time trial performed on track, which derived in an increase in GCT.

The severity of these fatigue manifestations does not only depend on the intensity and duration of the exercise, but also on the pattern of muscle activity where footwear has a determinant role. Over a 10-km treadmill run, Sanno et al.¹¹ observed a higher ankle negative work ($\sim 7\%$) when athletes used the Adidas Adizero Pro 4 racing flats compared to the Brooks Glycerin 10 cushioned model. After completing a marathon, a preliminary report¹² suggests that the use of the Nike Vaporfly 4 % resulted in a reduced muscle soreness and damage compared to the Nike Pegasus 34 conventional model. Likewise, Vercruyssen¹³ reported a greater calf pain after completing a trail course with the Salomon Sense minimal model compared to the Salomon XT Wings traditional model. Thus, it seems that the allostatic load of an equal effort in terms of duration and intensity can be modulated by the footwear used.

In self-paced long-distance efforts, these fatigue-related input signals are integrated by the central nervous system in order to ensure that the work rate can be sustained for the target distance to be covered, and thus homeostasis¹⁴. This is appreciable in the pacing strategies that athletes adopt, typically described as a “U-shape”, which has been used as an indicator of central fatigue. Dinato et al.⁷ analyzed the speed distribution that athletes adopted to complete a 3-km time trial on track with the Nike Free Run 2

minimal model and the Adidas Energy Boost cushioned model. Despite athletes showed a greater RE with the cushioned model ($\sim 2.4\%$), no significant interactions and main effects were observed in the pacing distribution and overall time.

Considering the recent advances implemented in the different types of footwear that athletes use for training and competing (i.e., route and track spikes models), it is necessary to analyze their effects on their different applications. In a competition context, a different fatigue evolution could determine the work capacity under reserve and thus performance on the last lap¹⁵. In a training context, practitioners need to be aware of the influence of footwear on the overall training load^{12,13}. Therefore, this study aims to compare the effect of the Nike ZoomX Dragonfly track spikes and the Nike ZoomX Vaporfly Next % 2 marathon shoes on the fatigue manifestations present over and after a typical long-distance track training session.

2. Materials and Methods

2.1 Experimental Design

A randomized crossover design was used to explore the effect of two different footwear categories (i.e., marathon shoes vs. track spikes) on the fatigue manifestations caused over and after a long-distance track training session. The athletes performed two maximal CMJs before and after completing two maximal efforts of 9- and 3-minutes with a full recovery between them. The pace, GCT, and SL evolution over each lap was monitored with the Stryd Power meter (Stryd Summit Power Meter, Boulder, CO, USA). Within one week, the same session was repeated with the corresponding footwear model. Of note, athletes were encouraged to release from vigorous activity in the previous 48 hours of each testing session. Both testing sessions were performed on an outdoor track

under similar environmental conditions ($\sim 22^{\circ}\text{C}$ and $\sim 40\%$ humidity, wind $< 10\text{ km/h}$) and time of day ($\pm 1\text{ hour}$).

2.2 Participants

A group of 13 highly trained male athletes (age: 26 ± 9 years, height: $178 \pm 4\text{ cm}$, body mass: $69 \pm 6\text{ kg}$; 3000 meters season-best: $09:06 \pm 00:21\text{ min:sec}$; training volume: 61 ± 23 kilometers per week) participated in the study. The following inclusion criteria were established to select highly trained athletes ¹⁶: (i) to perform a training volume of > 150 minutes per week, and (ii) to compete nationally. All participants were informed about the research purpose and procedures of the study before signing a written informed consent form. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the institutional review board (No. 2276/CEIH/2021).

2.3 Footwear conditions

The characteristics of the footwear are described in table 1. Based on the minimal index purposed by Esculier et al. ¹⁷, the track spikes and the marathon shoes present a minimalism level of 60 and 34 %, respectively. Both models were owned by athletes with the premise of not exceeding 50 kilometers of use. If not, a new pair of shoes were provided. Athletes were used to running with both footwear models as part of their training programs and competitions.

-Table 1 about here-

2.4 Long-distance track training session

The long-distance track training sessions were performed on the outdoor track of the University of Granada Sports Science Faculty. The track lap was 322 meters of distance. Athletes performed a standardized warm-up which consists of 10 minutes at

low-to-moderate intensity (i.e., intensity corresponding to easy long-running sessions). After a series of dynamic mobility exercises, 2-3 progressive high-intensity runs of 100 meters were done to complete the warm-up. Then, athletes firstly performed the 9 minutes time trial. After a 20-minute active rest period, athletes performed the 3 minutes time trial. The Borg's category-ratio 100 scale (CR-100)¹⁸ reported immediately after the long-distance track training session was used to determine the perceived effort.

2.5 Fatigue manifestations during the long-distance track training session

The fatigue manifestations during the long-distance track training session were examined through the analysis of the pace, GCT, and SL evolution at each minute during the 9- and 3-minutes time trials^{10,14}. The running power meter (Stryd Summit Power Meter, Boulder, CO, USA) was used to determine the aforementioned metrics validly and reliably¹⁹⁻²¹. Records were synchronized from the pod to the Stryd platform²² and then exported to an excel spreadsheet for subsequent analyses.

2.6 Fatigue manifestations after the long-distance track training session

The fatigue manifestations after the long-distance track training session were examined through the execution of two maximal CMJs before and after the training session with athletes' own training shoes (i.e., those used for warm-up). Before the CMJ test, five progressive jumps were performed as part of the specific warm-up. The CMJ technique involves athletes standing with the knee and hips fully extended, feet approximately shoulder-width apart, and the hands on the hips. From this position, they were required to jump as high as possible after performing a fast countermovement to a self-selected depth. Athletes were instructed to touch down the ground with extended leg in foot plantar flexion. The execution of the two maximal CMJs was interspaced with 1-minute rest before and after the training session. If there was a large variability between

them ($> 10\%$), a third trial was included to then select the maximum height achieved ²³. After the training session, athletes performed 5 minutes of active recovery before performing the two maximal CMJs again. A floor-level, high-density photoelectric cells (OptoGait; Microgate, Bolzano, Italy) were used to estimate the CMJ height by the flight time method, which has shown a high level of agreement with force plate measurements ²⁴.

2.7 Statistical analysis

Descriptive statistics are represented as mean $\pm$ standard deviation (SD). The normal distribution of data and homogeneity of variances were confirmed through the Shapiro-Wilk test and Levene's tests, respectively. A two-way repeated-measures analysis of variances (ANOVA) (footwear [track spikes *vs.* marathon shoes] x time trial [9 and 3 minutes]) with Bonferroni post-hoc test was applied to compare running performance in both time trials. A paired samples t-test was used to compare the perceived effort. A two-way repeated-measures ANOVA (footwear [track spikes *vs.* marathon shoes] x lap [each minute]) was applied to determine the evolution of the distance covered, GCT and SL in each lap during the long-distance track training session. A two-way repeated-measures ANOVA (footwear [track spikes *vs.* marathon shoes] x time [pre and post]) was applied to determine the evolution of the CMJ height after the long-distance track training session. The reliability of the CMJ height was determined as the mean intra-individual coefficient of variation (CV) between pre-test conditions ²⁵. Statistical significance was accepted at $p < 0.05$ level. Data analysis was performed using the software package SPSS (IBM SPSS version 25.0, SPSS Inc., Chicago, IL., USA).

3. Results

3.1 Fatigue manifestations during the long-distance track training session

There was no significant main effect of footwear ($F_{(1,12)} = 0.27$; $P = 0.613$) or footwear x time trial interaction ($F_{(1,12)} = 1.42$; $P = 0.257$) on the total distance covered (Track spikes: 2847 [30] and 1036 [10] meters; Marathon shoes: 2845 [30] and 1444 [12] meters). The lap analysis revealed a significant time effect in the 9 ($F_{(8,104)} = 12.4$; $P < 0.001$) and 3 ($F_{(2,24)} = 12.3$; $P < 0.001$) minutes time trials. No significant footwear x lap interaction was observed in both time trials (9 minutes: $F_{(8,104)} = 1.87$; $P = 0.072$; 3 minutes: $F_{(2,24)} = 1.73$; $P = 0.199$) (**Figure 1**). For the track spikes condition, the greatest pace drop occurred in the 6-7th minutes lap (-23.57 meters [95% CI: -41.86 to -5.28 meters]; -7.33 %) and in the 2-3rd minutes' lap (-16.92 meters [95% CI: -27.54 to -6.30 meters]; -4.91 %) with respect to the 0-1st minutes' lap. For the marathon shoes, the greatest pace drop occurred in the 7-8th minutes lap (-31.43 meters [95% CI: -62.23 to -0.60 meters]; -9.50 %) and in the 1-2nd minutes' lap (-13.85 meters [95% CI: -22.49 to -5.20 meters]; -4.00 %) with respect to the 0-1st minute lap. No significant differences were observed in the perceived effort (Track spikes: 99 [13]; Marathon shoes: 99 [15]; $p = 0.900$).

There was a significant main effect of footwear (9 minutes: ($F_{(1,12)} = 6.46$; $P = 0.025$) and 3 minutes: ($F_{(1,12)} = 16.7$; $P = 0.001$) indicating that GCT was overall increased when using the track spikes. No significant footwear x lap interaction was observed in both time trials (9 minutes: ($F_{(8,104)} = 1.46$; $P = 0.252$) and 3 minutes: ($F_{(2,24)} = 2.01$; $P = 0.052$). However, there was a significant time effect on GCT in the 9 ($F_{(8,104)} = 10.05$; $P < 0.001$) and 3 ($F_{(2,24)} = 11.51$; $P < 0.001$) minutes time trials. For the track spikes, the greatest increase occurred in the 6-7th minutes' lap (8.57 milliseconds [95% CI: 4.05 to 13.09 milliseconds]; 4.79 %) and in the 2-3rd minutes' lap (4.38 milliseconds [95% CI: 1.52 to 7.24 milliseconds]; 2.56 %) with respect to the 0-1st minutes' lap. For the marathon shoes, the greatest increase occurred in the 7-8th minutes' lap (11.79

milliseconds [95% CI: 3.36 to 20.21 milliseconds]; 6.79 %) and in the 1-2nd minutes' lap (3.85 milliseconds [95% CI: 1.16 to 6.53 milliseconds]; 2.29 %) with respect to the 0-1st minutes' lap.

No significant main effects of footwear (9 minutes: $F_{(1,13)} = 0.00$; $P = 0.984$; 3 minutes: $F_{(1,13)} = 3.26$; $P = 0.09$) and footwear x lap interaction (9 minutes: $F_{(8,104)} = 1.93$; $P = 0.063$; 3 minutes: $F_{(2,24)} = 1.21$; $P = 0.315$) were observed on SL. However, there was a significant time effect on SL in the 9 ($F_{(8,104)} = 9.82$; $P < 0.001$) and 3 ($F_{(2,24)} = 9.61$; $P = 0.001$) minutes time trials. For the track spikes, the greatest reduction occurred in the 6-7th minutes lap (-0.17 meters [95% CI: -0.34 to 0.00 meters]; -3.47 %) and in the 2-3rd minutes lap (-0.13 meters [95% CI: -0.22 to -0.04 meters]; 3.70 %). For the marathon shoes, the greatest reduction occurred in the 6-7th minutes' lap (-0.26 meters [95% CI: -0.49 to -0.03 meters]; -7.31 %) and in the 1-2nd minutes' lap (-0.09 meters [-95% CI: 0.17 to -0.02 meters]; 2.60 %).

-Figure 1 about here-

3.2 Fatigue manifestations after the long-distance track training session

An acceptable reliability was reported for the CMJ height ($CV = 4.15$ %). There was a significant footwear x time interaction ($F_{(1,12)} = 6.80$; $P = 0.023$) (**Table 2**). The CMJ height was reduced after completing the training session with the track spikes (-1.78 cm [95% CI: -3.02 to -0.53 cm]; -5.60 %) but not with the marathon shoes (0.28 cm [95% CI: -1.05 to 1.62 cm]; 0.61 %).

-Table 2 about here-

4. Discussion

This study was designed to compare the effect of two footwear models categorized as maximal (marathon shoes) and minimal (track spikes) on the fatigue manifestations present over and after a typical long-distance track training session. The results of the present study revealed that although there was no significant interaction in the pace distribution, athletes tend to be only able to increase the pace at the end of the session with the marathon shoes (3rd vs. 2nd lap: 5.4 meters [-3.7 to 14.5 meters]) meanwhile with the track spikes it further decreased (3rd vs. 2nd lap: -3.1 meters [-9.8 to 3.6 meters]). The reduced GCT over the session (9 minutes: -2.69 milliseconds [-4.98 to -0.40 milliseconds]; 3 minutes: -3.85 milliseconds [-5.89 to -1.79 milliseconds]) and the increased SL in the last time trial (0.08 meters [-0.02 to 0.17 meters]) indicate that the use of marathon shoes enables athletes to better tolerate a long-distance track training session, and in particular, the end of it. The reduction of the CMJ height (-5.60 %) after completing the training session with the track spikes compared to the maintenance (0.61 %) when using the marathon shoes also indicate that footwear influence the resulting allostatic load despite performing equal efforts in terms of duration and intensity.

Running velocity is determined by the sum of the ankle, knee, and hip positive works. However, their relative contribution differs considerably, being the ankle joint the greatest involved due to the lower metabolic cost ²⁶. This unproportioned positive work contribution has been established at long-distance ²⁶ (Ankle: ~ 50 %; Knee: ~ 30 %; Hip: ~ 20 %) and mid-distance efforts ²⁷ (Ankle: ~ 70 %; Knee: ~ 14 %; Hip: ~ 16 %), which leads to a sooner ankle fatigue and work redistribution to distal joints. The reduced GCT over the training session, and the appreciable increased SL at the last time trial when using the marathon shoes indicate that the plantar flexors were optimized, and thus probably the work redistribution. One of the recent advances applied to racing footwear has been

the so-called “teeter-totter” effect²⁸. This mechanism facilitates plantar flexion through a first-class lever created by the increased longitudinal bending stiffness and the curved geometry of the embedded carbon fiber plate²⁸. This mechanism is present in the footwear models tested, however, the lower heel and forefoot stack height of the track spikes (Marathon shoes: 40 – 32 mm; Track spikes: 20 – 20 mm) could have resulted in a less effective lever due to a reduced curved geometry of the carbon fiber plate. However, it is worth mentioning that flat carbon fiber plates have also shown to delay the positive work redistribution due to an enhanced energy return of the Achilles tendon and due to the optimized force-length and force-velocity profile of the gastrocnemius medialis as a result of the increased ankle external moment²⁹.

The differences between footwear models with different degrees of minimalism might be more appreciable in the negative work performed¹¹. This is derived due to the reduced peak dorsiflexion observed when using maximal models³⁰. Despite it has been shown that during the loading stance phase, athletes store energy through the ankle dorsiflexion, which results in a reduction of the positive work subsequently performed³¹, storing energy in passive structures requires an eccentric muscle contraction³² in which type II muscle fibers are more prone to muscle damage than type I³³. Thus, after an eccentric fatigue protocol (i.e., downhill running), RE has shown to be only impaired at high running intensities³⁴. The different stack heights and heel-toe drops of the models used in the present study (Marathon shoes: 40-32 mm; Track Spikes: 20-20 mm) could have resulted in different negative works performed over the training session, and thus, a greater demand of type II muscle fibers when using the track spikes which were also elicited due to the high intensities established.

The reduced CMJ height after completing the long-distance track training session also supports this hypothesis. However, the use of this test to determine neuromuscular

fatigue has been widely discussed ³⁵. It has been stated that the sensitivity of a neuromuscular test to determine fatigue after a stretch-shortening cycle exercise (i.e., running) relies on the eccentric component ³⁶. Thus, the CMJ has shown to be more susceptible to responding to an immediate fatigue evaluation than those relying less on (i.e., squat jump) ³⁶. Likewise, the eccentric load of the fatiguing protocol seems to also determine the CMJ height changes. A consistent reduction of the CMJ height has been observed during sprint training ^{9,37}, meanwhile its evolution has been more variable, increasing and decreasing after incremental protocols or long-distance races ^{38,39}. The intensities here established might have induced a sufficient eccentric load on the track spikes, but not in the marathon shoes to reduce the CMJ height.

Other studies have analyzed the effect of footwear on the resulting fatigue. Black et al. ⁴⁰ determined the influence of using a highly cushioned model on the muscle damage resulted after 30 minutes of downhill run at a moderate intensity compared to a control model with less compliant and resilient midsole properties. Although there was no significant main effect of footwear on the extent of muscle damage observed, the firstly improved RE (~ 3.2 %) with the highly cushioned model was further reduced 48 hours after (~ 4.6 %) ⁴⁰. Likewise, Vercruyssen et al. ¹³ observed a greater RE deterioration when using the Salomon Sense minimal model compared to the Salomon XT traditional model after completing a trail running course. The different fatigue manifestations observed could have a great implication on the training context. In a recent report, it was determined that youth athletes who trained with track spikes increased six times the risk of a first injury compared to those that did the same training volume without using track spikes ⁴¹. The main cause of developing an injury was overuse ⁴¹, which leads athletes and practitioners to be aware of the influence of footwear on the overall training load.

Finally, there are a few limitations that should be highlighted. First, the fatigue manifestations are conditioned to the footwear models used. Ruiz-Alias et al.² highlighted the wide variability that the different footwear categories (i.e., marathon shoes, minimal shoes, maximal shoes) present based on the models compared on RE, performance and biomechanics. Thus, further track spikes and marathon shoes models need to be evaluated. Second, the athletes here recruited were highly trained and they were used to both types of footwear at the moment of evaluation. Thus, it should be noted that recreational athletes might respond differently, and these fatigue manifestations might be more marked in the early stages of track spike use in the season. Lastly, athletes completed ~ 4000 meters at an intensity within the severe intensity domain⁴², which remains unknown how these differences between footwear would be at higher training volumes and at the different intensity domains.

5. Conclusions

The type of footwear selected to complete a long-distance track training session seems to influence the resulting fatigue. Using the Nike ZoomX Vaporfly Next % 2 marathon shoes resulted in a reduced GCT over the session, and a trend towards increasing SL at the end of it allowing to increase the pace in the last lap compared to the Nike ZoomX Dragonfly track spikes. The reduction of the CMJ height after completing the training session with the track spikes compared to the maintenance when using the marathon shoes also indicate that footwear influences the training load.

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Table 1. Footwear characteristics.

	Maximal shoes	Minimal shoes
Model	Nike ZoomX Varpofly Next % 2	Nike ZoomX Dragonfly
Weight (43 EU)	196 grams	139 grams
Stack height	40 mm	20 mm
Heel to toe drop	8 mm	< 1 mm
Motion control	Heel counter and insole medial arch	Insole medial arch
Longitudinal flexibility	Extreme	Extreme
Torsional flexibility	Very high	Extreme

Table 2. Countermovement jump height evolution after completing the long-distance track training session with track spikes and marathon shoes.

CMJ		Track Spikes			Marathon shoes				ANOVA	
CV (%)	Pre	Post	Mean	%	Pre	Post	Mean	%	Time effect	Footwear x time interaction
			change				change			
			(95% CI)				(95% CI)			
4.15	28.97	27.19	-1.78		28.23	28.52	0.28			
			(-3.02 to -	-5.60			(-1.05 to	0.61	0.117	0.023
	(5.35)	(4.55)	0.53)		(3.89)	(5.16)	1.62)			

CMJ: Countermovement jump; CV: Coefficient of variation; CI: Confidence interval

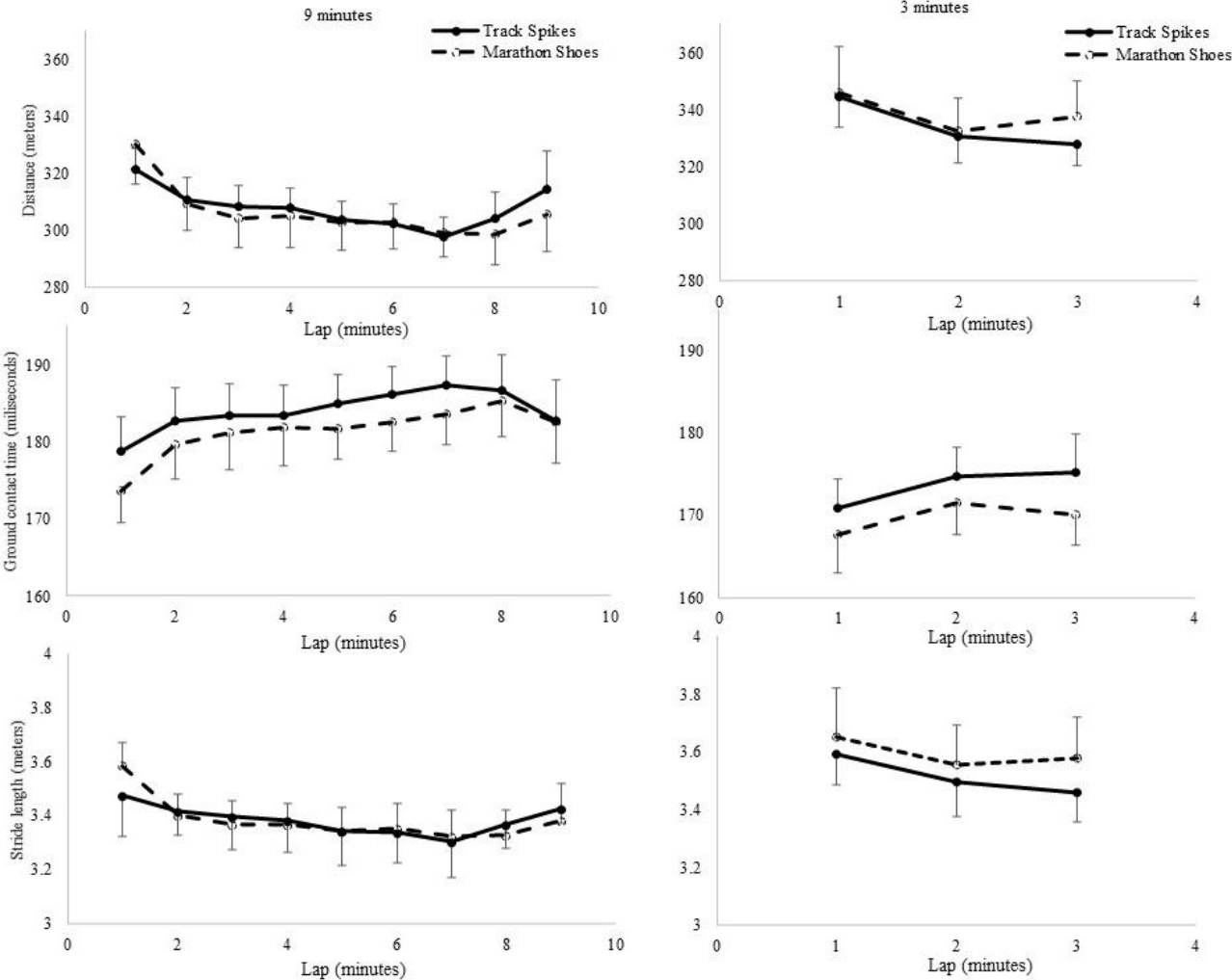


Figure 1. Distance, ground contact time and stride length evolution during the 9- and 3- minutes time trials when using track spikes and marathon shoes.

Artículo 5: Estudio experimental sobre el efecto de la geometría de la placa de carbono en el rendimiento y la economía de carrera en distintos grados de fatiga

Influence of the carbon fiber plate curvature of advanced footwear technology on the running energetic cost and 3000-m performance

Running head: Low versus high curvature plate geometry

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Abstract

This study aimed to explore the effect of two similar commercialized advanced footwear technology models differing mainly in their plate geometry (i.e., low and high curvature plate) on the running energetic cost in both non-fatigued and fatigued states. It also sought to determine their impacts on 3000-m performance. Twelve highly trained male athletes performed four 5-min trials (two advanced technology models, two trials). In each experimental session, athletes completed a 3000-m trial which was followed by a 5-min trial to test the running energetic cost when fatigued. Athletes exhibited a lower running energetic cost when wearing the low curvature plate in a non-fatigued state ($P = 0.034$; -1.13 [-1.92 to -0.11] %), which persisted with better performance in the 3000-m trial ($P = 0.017$; -0.42 [-0.74 to -0.09] %). However, in a fatigued state, non-significant differences were reported ($P = 0.207$). The low curvature plate seems to be more effective than the high curvature plate when running at low intensity in a fresh state as well as in a maximal high-intensity effort. However, non-significant differences between plate geometries were observed when fatigue was increased.

Keywords: Road shoes, advanced footwear technology, running economy, running performance, fatigue.

Introduction

During each stride, about 80% of the overall energetic cost is oriented to meet the mechanical work demanded for the body weight support and forward propulsion [1, 2]. For this demanding task, the hip, knee and ankle joints distribute the mechanical work, although not in a uniform fashion, being of about 20, 30 and 50% [3] in the respective joints, and raise even more to the distal joint (~70%) when the running intensity increases [4]. Accordingly, enhancing the balance of mechanical and energetic work at the ankle joint has become a relevant issue, particularly, from the perspective of footwear design through the increase of the longitudinal bending stiffness in the so-called advanced footwear technology (AFT) [5].

From the various of carbon fiber-reinforced composite materials used for this aim, two mechanisms could be differentiated. On the one hand, adding elements such as a low curvature plate (LCP) within the midsole increases the ankle push-off moment [6]. This creates an increased gear ratio between the external and internal ankle moments, reducing the ankle angular velocity [6]. This reduction could optimize the force-velocity profile of the triceps surae by reducing the mean shortening velocity, an aspect that would theoretically lower the motor unit recruitment and therefore the metabolic demand [7]. Moreover, Cigoja et al. [8] reported that this footwear feature significantly engages the Achilles tendon, thereby increasing the non-taxing force generation of the triceps surae. However, athletes may experience a detrimental effect on their running energetic cost if their strength capacities are limited [6]. On the other hand, adding elements such as a high curvature plate (HCP) can reduce the ankle push-off moment by shortening the lever arm [9]. Additionally, Nigg et al. [10] suggest that an upward reaction force could be created at the rearfoot region when the ground reaction force travels forward during the end of

the stance phase. This might create a “teeter-totter effect” that facilitates ankle plantar flexion [10], although the current evidence of this mechanism is lacking [11].

In this regard, Rodrigo-Carranza et al. [12] have performed a meta-analysis integrating those studies comparing the effect of AFT with a HCP with respect to no-plate conditions on the running energetic cost, reporting a ~3.5% improvement. However, to the authors' knowledge, no studies have compared the effect of AFT with different plate geometries on the running energetic cost and performance. This latter variable has been scarcely analyzed in the running footwear field as Fuller et al. [13] and later Ruiz-Alias et al. [14] highlighted. This is of particular interest for determining the effectiveness of a plate geometry since measurements of the running energetic cost are limited to intensities under the lactate threshold (LT) [15]. Superior running intensities could compromise to a greater extent the ankle plantar flexor force-velocity demands [2, 7], at which it is hypothesized that a LCP would report superior benefits than a HCP [16]. Likewise, with the onset of fatigue, it has been observed that the positive work shifts from distal to proximal joints during a prolonged run [3], and this can be delayed by increasing the longitudinal bending stiffness of the footwear [17], although it is unknown through which geometry it would be further improved.

With the continuous development of AFT, athletes nowadays have the option of using similar commercialized models differing mainly in the curvature of the plate. Therefore, this study aims i) to explore the effect of two similar commercialized AFT models differing mainly in their plate geometry (i.e., HCP, LCP) on the running energetic cost in non-fatigued and fatigued states, and ii) to determine their effects on the 3000-m performance.

Methods

Experimental design

A randomized crossover design was used to explore the effect of two similar commercialized AFT models differing mainly in their plate geometry (i.e., HCP, LCP) on the running energetic cost in non-fatigued and fatigued states and on the 3000-m performance. On the first testing session, athletes performed a graded exercise test in which the LT, lactate turn point (LTP), first and second ventilatory thresholds (VT1, VT2), and the maximum oxygen uptake ($\dot{V}O_{2\max}$) were determined. On the second and third testing sessions, athletes performed two 5-min trials at the speed associated with the LT/VT1, interspersed by 5-min rest, in which both footwear models were used in a randomized counterbalanced order. Then, athletes performed a 3000-m trial at the speed associated with the $\dot{V}O_{2\max}$ (i.e., maximal aerobic speed [MAS]). After 10-min rest, athletes performed a 5-min trial with the footwear used in the 3000-m trial to test the running energetic cost in a fatigued state. All testing sessions were performed on a treadmill under similar environmental conditions ($\sim 22^{\circ}\text{C}$ and $\sim 40\%$ humidity) and time of day (± 1 hour) (**Figure 1**).

-Figure 1 about here-

Participants

Twelve highly trained male athletes (age: 25 ± 6 years, height: 178 ± 4 cm, body mass: 67 ± 6 kg; 3000-m season-best: $08:49 \pm 00:24$ min:ss; training volume: 90 ± 22 kilometers per week; $\dot{V}O_{2\max}$: 62.5 ± 6.2 ml/kg/min) participated in the study. Our sample size was based on previous studies that for an expected biological and technological error of 1.5-2.0% for measurements of the oxygen uptake [18], a sample size of 9-12 athletes

enabled to discern a 1-2% mean difference between conditions ($1-\beta$: 0.6 to 0.8) [19–21]. Athletes were recruited based on shoe size (9 US) and 3000-m season-best time ($< 09:30$ mm:ss). The non-fatigued energetic cost trials were performed by the twelve athletes recruited. However, for the 3000-m and the fatigued energetic cost trials, three athletes were discarded after checking the exclusion criterion of maximal effort (i.e., the $\dot{V}O_{2peak}$ reached on each 3000-m trial were compared with the $\dot{V}O_{2peak}$ reached at the graded exercise test in order to confirm the $\dot{V}O_{2max}$ and guarantee a maximal effort in both 3000-m trials). All athletes were informed about the research purpose and procedures of the study before signing a written informed consent form. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the institutional review board (No. 2276/CEIH/2021).

Footwear models

The Asics Metaspeed Edge+ (HCP) and the Asics Metaspeed Sky+ (LCP) models were used. Both AFT models present the same midsole material (i.e., Flyte Foam) and similar shoe mass (HCP: ~212 grams; LCP: ~208 grams). These differ in the carbon fiber-reinforced composite plate and forefoot midsole geometries (i.e., forefoot stack height, rocker and drop) (see **Figure 2** for further details).

-Figure 2 about here-

Graded exercise test

The graded exercise test was conducted on a treadmill (WOODWAY Pro XL, Woodway, Inc., Waukesha, WI, USA). Athletes wore their own shoes. The test comprised 3-min stages with speed increments of 1 km/h, interspersed by 30-s rest in which a fingertip capillary blood sample was collected for the subsequent analysis of lactate

(Lactate Scout, SensLab GmbH, Germany). The starting speed was customized according to the athlete's training history and recent performance. Athletes were asked to exert a maximum effort. The test was finished when they could not complete a stage or declined to start a new one. The portable metabolic analyzer (COSMED K5, Rome, Italy) [22] was used to determine the VT1 and VT2, as well as the $\dot{V}O_{2\max}$ and MAS. The metabolic analyzer was calibrated following the manufacturer's recommendations [22].

The blood lactate values were plotted against the running speed to determine the LT and the LTP by visual inspection [23]. The LT was established at the first breakpoint, where blood lactate concentration rises above the baseline value. The LTP was established at the second disproportionate increase in the lactate–speed relationship. The breath-by-breath data were examined to exclude errant breaths and those values outlying more than four standard deviations from the local mean were removed. Then, data were linearly interpolated to give 1-s values and then averaged into 10-s time bins. The smoothed breath-by-breath data were plotted against the running speed for determining the VT1 and VT2 [24]. The VT1 was defined as the minimal speed at which the ventilatory equivalent for oxygen exhibited a systematic increase without a parallel increase of the equivalent for carbon dioxide. The VT2 was established as the minimal speed at which the increase of both ventilatory equivalents occurs. Both methods (i.e., lactate and ventilatory measures) were used to determine each intensity domain landmark, although the ventilatory analysis was always prioritized. The $\dot{V}O_{2\max}$ and MAS were determined as the highest 30-s rolling mean value and the speed associated, respectively. Two independent researchers followed the aforementioned procedure and reached a final agreement to establish each intensity domain landmark, the running speed at which the energetic cost was tested (i.e., LT/VT1), the initial pace to establish in the 3000-m trial (i.e., between

VT2/LTP and MAS), and maximal effort criterion to reach in each 3000-m trial (i.e., $\dot{V}O_{2\max}$).

Running energetic cost

Athletes performed two 5-min trials at the speed associated with the LT/VT1 (15.6 ± 1.0 km/h or 80.2 ± 7.6 % $\dot{V}O_{2\max}$), interspersed by 5-min rest, in which both footwear models were used in a randomized order, and counterbalanced on the following testing session. After the 3000-m trial, athletes rested for 10-min and completed a third 5-min trial with the footwear used in the 3000-m trial. The mean oxygen uptake and dioxide production of the last 2-min of each trial were used to calculate the energetic cost (W/kg) using the Brockway equation [25]. A steady metabolic state was required to compare each footwear condition (Respiratory exchange ratio [RER] < 1.0) which was met for each day and condition (HCP day 1: 0.91 ± 0.06 ; LCP day 1: 0.90 ± 0.07 ; HCP day 2: 0.89 ± 0.08 ; LCP day 2: 0.90 ± 0.07 ; LCP post 3000-m: 0.85 ± 0.08 ; HCP post 3000-m: 0.85 ± 0.08). The mean biological and technological error for the energetic cost of running was determined with the data obtained on days 1 and 2 (i.e., 1.7 %). This one was calculated as follows: standard deviation (SD) (Day 1 and Day 2) / $\sqrt{2}$, and expressed as a % of the mean (Day 1 and Day 2).

3000-m trial

The 3000-m trial was performed on a treadmill. Based on the results of the graded exercise test, the starting velocities of the 3000-m trials were proposed to be at MAS, or in consensus with the athlete according to their severe intensity domain range (i.e., between LTP/VT2 and MAS). Athletes were asked to exert a maximum effort and to self-regulate their pace. With a thumb-up or -down signal, the athletes indicated to the

researcher whether to modify their pace ± 0.5 km/h. The $\dot{V}O_{2\text{peaks}}$ reached on each 3000-m trial were compared with the $\dot{V}O_{2\text{peak}}$ reached at the graded exercise test to confirm the $\dot{V}O_{2\text{max}}$ and guarantee a maximal effort in both 3000-m trials.

Statistical analysis

Descriptive statistics are represented as mean $\pm$ SD. The normal distribution of data and homogeneity of variances were confirmed through the Shapiro-Wilk test and Levene's tests, respectively. A paired-sample *t*-test was used to compare the running energetic cost and 3000-m performance between both AFT models. Data analysis was performed using the software package SPSS (IBM SPSS version 25, SPSS Inc., Chicago, IL., USA). Statistical significance was set at $P < 0.05$.

Results

Running energetic cost

There was a significant difference in the running energetic cost ($P = 0.034$) (**Table 1**). Athletes exhibited a lower running energetic cost with the LCP model (-0.20 [-0.35 to -0.02] W/kg; -1.13 [-1.92 to -0.11] %). After completing the 3000-m trial, the running energetic cost was not significantly different between footwear models ($P = 0.207$) (**Figure 3**).

-Table 1 about here-

-Figure 3 about here-

3000-m performance

There was a significant difference in the 3000-m performance ($P = 0.017$) (**Table 1**). Athletes exhibited a lower time with the LCP model (-2.33 [-4.14 to -0.53] sec; -0.42 [-0.74 to -0.09] %).

Discussion

The results revealed that athletes exhibited a lower running energetic cost with the LCP model in a non-fatigued state and better performance in the 3000-m trial. However, non-significant differences were observed between models in the running energetic cost in a fatigued state.

Although the acting mechanisms of HCP and LCP have been widely exposed in the literature [6, 10], the existing evidence of their benefits with respect to a no plate condition is inconsistent [11]. On the one hand, Rodrigo-Carranza et al. [26] conducted a meta-analysis in which those studies analyzing the effects of a HCP model (i.e., Nike Vaporfly 4%) with respect to no plate models on running economy were included, observing a mean improvement of $\sim 3.5\%$. However, Healey and Hoogkamer [27] reported later that reducing the stiffness of this HCP model through 6 medio-lateral cuts did not impair the running economy with respect the same model in its intact state, suggesting that metabolic savings result from the interaction of the rest of the footwear features (i.e., midsole foam, geometry). On the other hand, Rodrigo-Carranza et al [26] also conducted a subgroup analysis for those studies analyzing the effect of LCP models with respect no plate models on running economy, observing non-significant differences. In this regard, Willwacher et al. [28] stated that the potential cause of not responding to this footwear feature could be related to how athletes adapt their running form to an increased lever arm at the ankle joint. Specifically, they observed that some athletes

increased their ankle joint moments while keeping push-off times, meanwhile others decreased ankle joint moments while increasing push-off times [28].

According to the existing evidence, it was necessary to determine the potential discrepancies and similarities between plate geometries to further understand the plate effectiveness. To do so, it was also of paramount importance to address their comparison in two contexts scarcely analyzed in the running footwear science field [14, 15, 29], at high-intensity efforts, and under fatigue. The methodological requirements of running economy measurements (i.e., intensities under the LT/VT1) in conjunction with testing different footwear conditions within a session (i.e., long recovery periods to change footwear) results in a submaximal assessment context, which differs from the AFT use in competition.

In this regard, athletes significantly improved their 3000-m times when using the LCP with respect the HCP. The potential sources of such differences could be related to the greater ankle joint moments and the resulting changes in the muscle function, which could be operating at a lower shortening velocity [30]. Although the 3000-m improvements were a matter of few seconds, it resulted in worthwhile differences from the practical standpoint, and was comparable to the effects of other footwear features. In this regard, Hoogakmer et al. [31] reported a $\sim 0.8\%$ improvement in 3000-m performance when reducing the shoe mass by 100 grams in a group of recreational runners. Likewise, Rodrigo-Carranza et al. [32] observed that a HCP provided an improvement of ~ 0.8 to 0.9% in 3000-m performance with respect to the same model without a plate in a group of recreationally and highly trained athletes.

Likewise, athletes displayed a better running economy when using the LCP with respect to the HCP, although after the 3000-m trial, no significant differences were observed between conditions. In this regard, it should be noted that the running economy

deteriorates with the onset of fatigue, which seems to be related to a redistribution of the lower limbs' work from distal to the more demanding proximal joints [17]. Although a LCP has been shown to delay the onset of work redistribution with respect to a no plate condition during a prolonged run (i.e., 10-km at 90% of the LT) [17], no significant improvements were seen in our study with respect the HCP. Further explorations with regard to the fatigue conditioning stimulus are required to fully understand the plate role in this function.

It is also important to acknowledge certain limitations. Firstly, despite our initial sample size was adequate for identifying 1-2% differences between conditions [19–21], the exclusion of three participants due to meeting the criterion of maximality possibly weakened our statistical power, affecting the accuracy of performance and running economy measurements under fatigue. Secondly, adding a control condition (without plate) would have provided an intriguing comparative to fully understand the performance implications of this footwear feature. However, no commercialized AFT models maintaining the same design without a plate were available. Also, arranging a third maximal testing session for the highly-trained athletes recruited presented logistical challenges due to their competition schedules. Thirdly, a single trial was performed in the fatigued state in pursuit of the athletes' comfort which restricted us to conducting an individual analysis [33]. This is a relevant issue given the comparison of a single trial could result in different outcomes compared to when multiple trials are averaged due to the biological and technological errors [33]. Therefore, only the group response was here reported. Lastly, only highly trained male athletes were recruited, limiting the extrapolation of these results to other populations, such as recreational runners, who may respond differently to AFT [32].

Conclusion

The LCP model reduced the running energetic cost in a non-fatigued state, and these benefits persisted in the 3000-m trial. However, in a fatigued state, no significant differences between plate geometries were observed. From a practical standpoint, these results suggest a promising perspective on the individualized use of running shoes.

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Conflict of Interest

The authors declare no conflict of interest.

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Table 1. Effect of the footwear models on the running energetic cost at the intensity associated to the first ventilatory threshold previously and after performing the 3000-m trial and on running performance.

	Variable	HCP	LCP	Δ	Δ (%)	P-value
Running energetic cost	Pre (n=12)	17.7 $\pm$ 2.0	17.5 $\pm$ 2.0	-0.20 (-0.35 to -0.02)	-1.13 (-1.92 to -0.11)	0.034
	(W/kg) Post (n=9)	17.2 $\pm$ 2.4	17.6 $\pm$ 2.2	0.41 (-0.28 to 1.11)	2.38 (-1.63 to 6.45)	0.207
Running energetic cost	Pre (n=12)	68.0 $\pm$ 6.1	67.3 $\pm$ 6.0	-0.72 (-1.35 to 0.09)	-1.05 (-1.99 to -0.10)	0.029
	(W/kg/km) Post (n=9)	65.5 $\pm$ 8.0	67.0 $\pm$ 6.4	1.56 (-1.17 to 4.31)	2.75 (-1.40 to 6.88)	0.225
Running performance	3000-m (n=9)	560 $\pm$ 31	558 $\pm$ 31	-2.33 (-4.14 to -0.53)	-0.42 (-0.09 to -0.74)	0.017
	(sec and $\dot{V}O_{2max}$ (n=9)	60.7 $\pm$ 7.2	61.4 $\pm$ 8.0	-0.63 (-4.18 to 2.92)	-1.04 (-6.92 to 4.81)	0.688
ml/kg/min)						

HCP: High curvature plate; LCP: Low curvature plate; $\dot{V}O_{2max}$: Maximum oxygen uptake; Δ : (HCP+-LCP)/HCP+*100

Figure 1. Experimental design. LT: Lactate threshold; LTP: Lactate turn point; VT1: First ventilatory threshold; VT2: Second ventilatory threshold; $\dot{V}O_{2max}$: Maximum oxygen uptake, MAS: Maximal aerobic speed. LCP: Low curvature plate; HCP: High curvature plate.

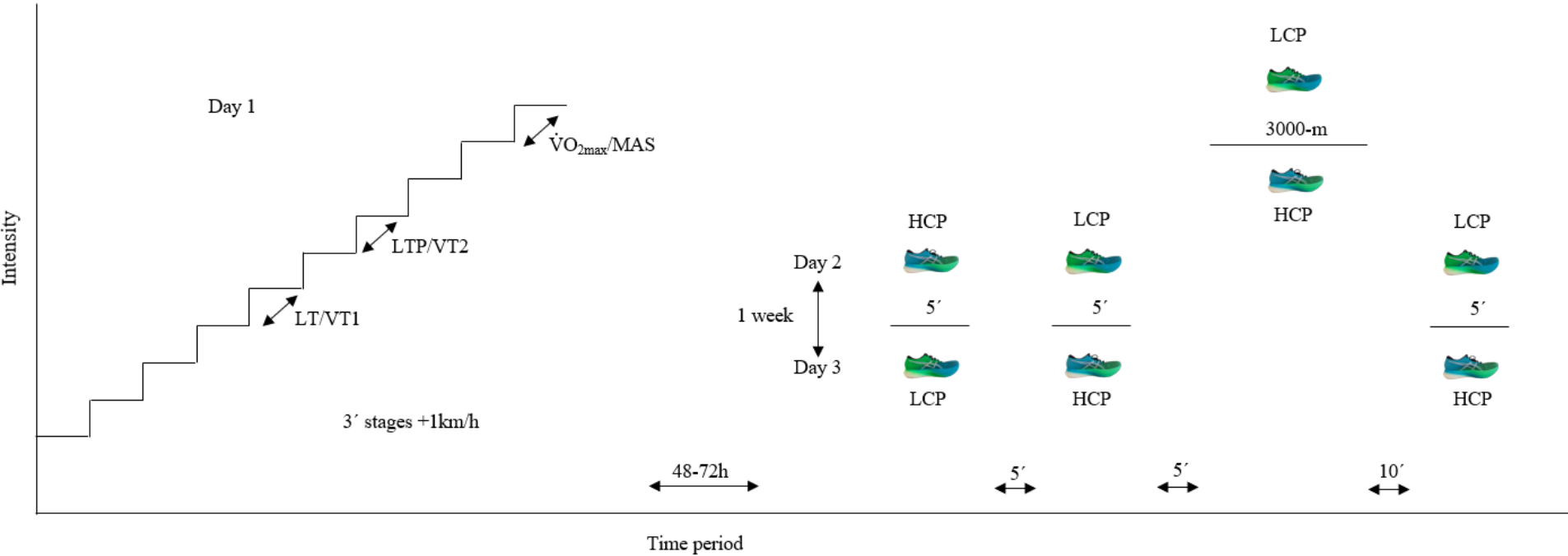


Figure 2. Characteristics of the racing footwear models. Shoe mass: 208 (LCP) vs. 212 (HCP) grams; Rearfoot stack height: 39 mm (LCP and HCP); Forefoot stack height: 34 mm (LCP), 31 mm (HCP); Rocker axis: 73 (LCP) vs. 70 (HCP) %; Rocker radius: 8.1 (LCP) vs. 9.5 (HCP) cm; Stiffness: Extreme resistance (LCP) vs. extreme resistance (HCP) [34]. The rocker axis and radius were determined with the free-access software Kinovea [35].

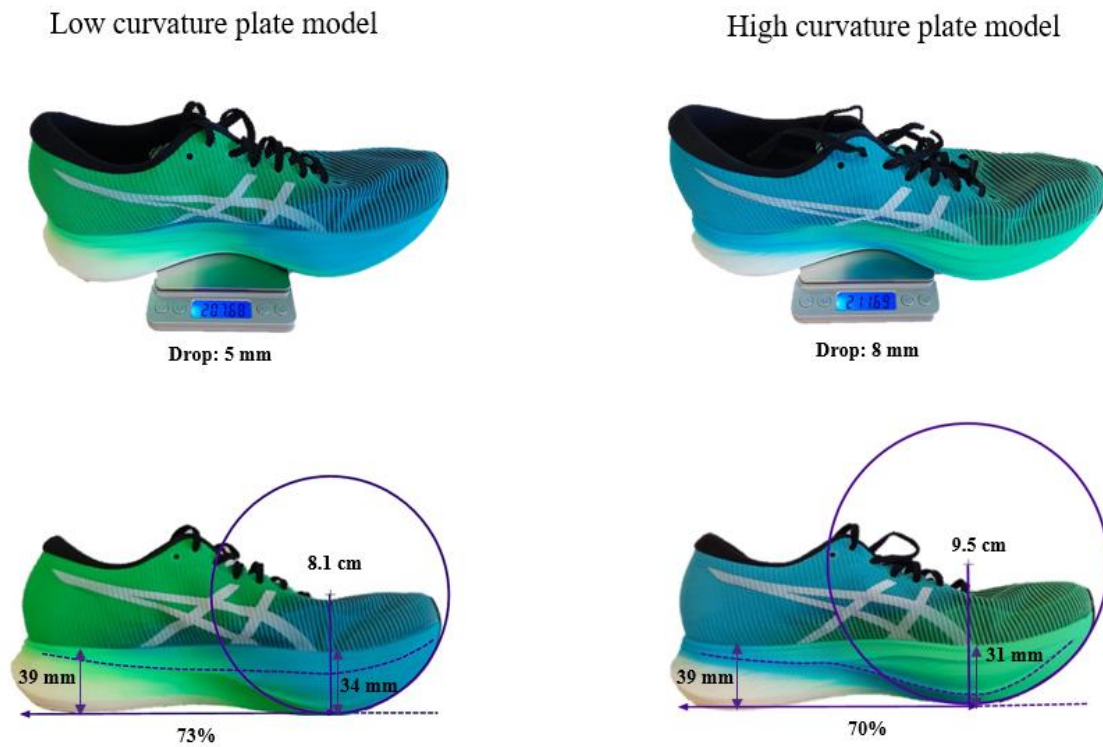
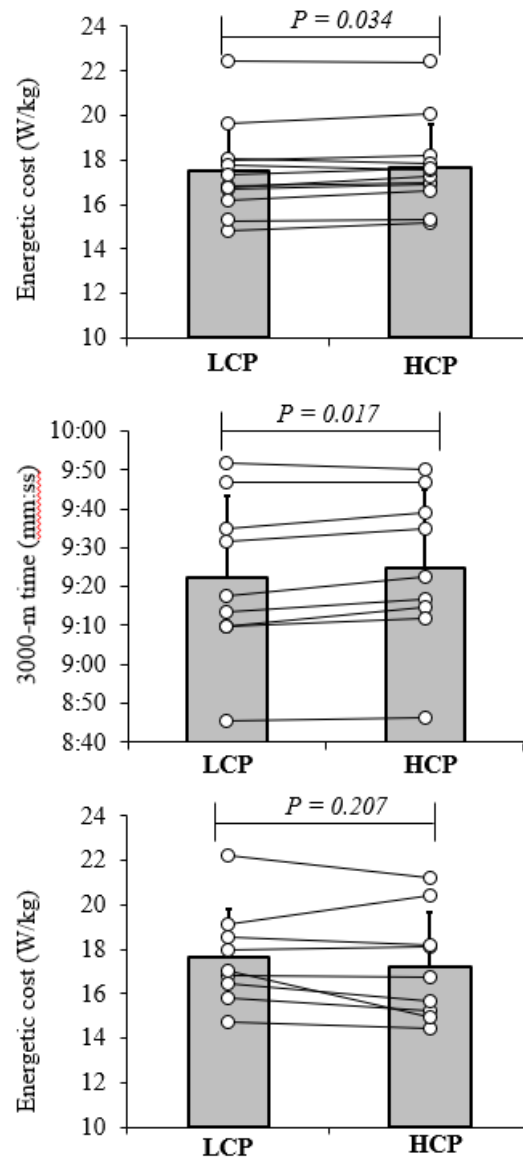


Figure 3. Group and individual responses to the racing footwear models on the running energetic cost tested previously and after performing the 3000-m trial and on running performance. LCP: Low curvature plate; HCP: High curvature plate; *: Athletes did not meet the maximal effort criterion.



Conclusiones

- El calzado categorizado por la regulación de la World Athletics por ilegal dio lugar a la mejora del rendimiento en carrera en pista respecto a un calzado legal en la prueba de tiempo de mayor intensidad (i.e., 3-min).
- Dichas mejoras se manifestaron desde el punto de vista mecánico en una reducción promedio de los tiempos de contacto. Asimismo, el análisis de la evolución de los parámetros espaciotemporales manifestó una tendencia progresiva a reducir la longitud de zancada y a aumentar los tiempos de contacto durante el transcurso de la prueba de 3-min con el calzado legal, mientras que con el calzado ilegal estos se mantuvieron. La fatiga neuromuscular también se manifestó en una caída del salto en contramovimiento al finalizar la sesión con el calzado legal, pero no así con el calzado ilegal.
- La geometría de la placa de carbono tiene un efecto significativo en el rendimiento del atleta en función del contexto. Específicamente, una geometría plana favorece la EC respecto a una geometría curva en un estado sin fatiga. Dicha mejora también se traduce a una mejora del rendimiento en 3000-m. Sin embargo, en un estado de fatiga, los atletas muestran una EC similar, siendo la geometría de la placa irrelevante en este contexto.

Conclusions

- The footwear categorized by the World Athletics regulation as illegal resulted in an improved track running performance with respect to the legal footwear in the time trial of highest intensity (i.e., 3-min).
- These improvements were manifested from the mechanical point of view in a mean reduction of the ground contact times. Likewise, the analysis of the evolution of the spatiotemporal parameters revealed a tendency towards progressively reducing the step length and increasing the ground contact times during the 3-min time trial with the legal footwear, meanwhile with the illegal one, these were maintained. The neuromuscular fatigue was also manifested in a drop of the countermovement jump at the end of the session with the legal footwear, but not with the illegal one.
- The geometry of the carbon fiber plate has a significant performance effect on the athlete's performance according to the context. Specifically, a flat geometry improved the EC with respect to a curved geometry in a non-fatigued state. This improvement was also present in the 3000-m trial. However, in a fatigued state, athletes displayed a similar EC, being the plate geometry irrelevant in this context.

Curriculum Vitae

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- Estancia de investigación en la Universidad Central Lancashire (Preston, UK) (1 de Mayo al 31 de Julio de 2022).
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Participación en proyectos de investigación

- Factores determinantes de la potencia crítica y del rendimiento en pruebas de carrera de 3000 y 10000 metros lisos (PPJIA2022-02). Universidad de Granada. (Enero a Diciembre de 2023).
- Desarrollo de una plataforma digital que permita monitorizar indicadores de rendimiento y salud deportiva para población andaluza involucrada en deporte federado y en programas de ejercicio físico saludable (EXP_74829). Ministerio de Cultura y Deporte. (Marzo a Noviembre de 2023).
- Prevención de lesiones en corredores de resistencia (Nº 5562). Instituto Andaluz del Deporte. (Noviembre de 2022 a Noviembre de 2023).

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Aportaciones a congresos

1. **Título de la aportación:** Funciones del calzado deportivo de carrera

Nombre del congreso: I Jornada Running Science

Tipo de aportación: Ponencia invitada

Ámbito: Nacional

Año: 2024

Lugar: Zaragoza, España

Autores: Ruiz-Alias, S. A.

2. **Título de la aportación:** ¿Cómo predecir el rendimiento en carrera?

Nombre del congreso: I Jornada Running Science

Tipo de aportación: Ponencia invitada

Ámbito: Nacional

Año: 2024

Lugar: Zaragoza, España

Autores: Ruiz-Alias, S. A.

3. Título de la aportación: Efectos de Diferentes Protocolos de Carrera de Alta Intensidad sobre el Rendimiento en el Entrenamiento de Fuerza.

Nombre del congreso: XII Congreso Internacional de la Asociación Española de Ciencias del Deporte.

Tipo de aportación: Póster

Ámbito: Internacional

Año: 2023

Lugar: Madrid, España

Autores: Pérez-Castilla, A., Ruiz-Alias, S.A., García-Pinillos, F.

4. Título de la aportación: Influencia del Calzado Deportivo en la Ejecución del Peso Muerto Convencional.

Nombre del congreso: I Congreso Internacional Optimización del Entrenamiento de Fuerza y Rendimiento Neuromuscular

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2022

Lugar: Granada, España

Autores: Ruiz-Alias, S.A., Butters, B., Sinclair, J.E.L.

5. Título de la aportación: The influence of menstrual cycle phase on maximal neuromuscular capacities of lower-body muscles: a pilot study.

Nombre del congreso: I Congreso Internacional Optimización del Entrenamiento de Fuerza y Rendimiento Neuromuscular

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2022

Lugar: Granada, España

Autores: Morenas-Aguilar, M.D., Pérez-Castilla, A., García-Pinillos, F., **Ruiz-Alias, S.A.**, Fernández-Navarrete, I., Moreno-Ortega, C., Marcos-Blanco, A.

6. Título de la aportación: Influencia del Calzado de Carrera en diferentes Manifestaciones de Fatiga Durante y Tras una Sesión de Entrenamiento de Larga Distancia.

Nombre del congreso: I Congreso Pleokinetics

Tipo de aportación: Comunicación oral

Ámbito: Nacional

Año: 2022

Lugar: Granada, España

Autores: **Ruiz-Alias, S.A.**, Soto-Hermoso, V.M., García-Pinillos, F.

7. Título de la aportación: Entrenamiento Concurrente: Influencia de la Secuencia de Ejercicios sobre las Adaptaciones en los Componentes del Fitness.

Nombre del congreso: II Congreso Investigación PTS

Tipo de aportación: Comunicación oral

Ámbito: Nacional

Año: 2022

Lugar: Granada, España

Autores: **Ruiz-Alias, S.A.**, Ruiz-Malagón, E.J., Marcos-Blanco, A., Soto-Hermoso, V.M., García-Pinillos, F.

8. **Título de la aportación:** Validez y fiabilidad de los sensores inerciales notch para medir el ángulo del codo durante derecha de tenis a diferentes frecuencias de muestreo.

Nombre del congreso: II Congreso Investigación PTS

Tipo de aportación: Comunicación oral

Ámbito: Nacional

Año: 2022

Lugar: Granada, España

Autores: Ruiz-Malagón, E.J.; Delgado-García, G.; Castro-Infantes, S.; Ritacco-Real, M.; Ruiz-Alias, S.A.; Soto-Hermoso, V.M.

9. **Título de la aportación:** Influencia del Calzado en el Rendimiento Deportivo.

Nombre del congreso: XLII Congreso de la Sociedad Ibérica de Biomecánica y Biomateriales.

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2019

Lugar: Madrid, España

Autores: Ruiz-Alias, S.A., Ruiz-Malagón, E.J, Delgado-García, G., Molina-Molina, A., Soto-Hermoso, V.M.

10. **Título de la aportación:** Validación del Medidor de Frecuencia Cardíaca del Nuevo Polar Vantage M. Estudio Piloto.

Nombre del congreso: XLII Congreso de la Sociedad Ibérica de Biomecánica y Biomateriales.

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2019

Lugar: Madrid, España

Autores: Ruiz-Malagón, E.J, **Ruiz-Alias, S.A.** Delgado-García, G., Soto-Hermoso, V.M.

11. Título de la aportación: Estimando las Repeticiones en Reserva: Influencia del Descanso entre Repeticiones, Carga Relativa y Proximidad al Fallo Muscular.

Nombre del congreso: II Congreso Internacional sobre Optimización del Entrenamiento de Fuerza y Rendimiento Neuromuscular.

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2023

Lugar: Madrid, España

Autores: **Ruiz-Alias, S.A.**, Pérez-Castilla, A., García-Pinillos, F., Quidel-Catrilebún, E.L.

12. Título de la aportación: Efecto agudo del entrenamiento de fuerza basado en la velocidad sobre el rendimiento en carrera posterior: Relevancia del volumen y de la intensidad.

Nombre del congreso: II Congreso Internacional sobre Optimización del Entrenamiento de Fuerza y Rendimiento Neuromuscular.

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2023

Lugar: Madrid, España

Autores: Pérez Castilla, A., Marcos-Blanco, A., **Ruiz-Alias, S.A.**, Ramírez-Campillo, R., Miras-Moreno, S., García-Pinillos, F.

13. Título de la aportación: ¿Plana o curva? Influencia de la Geometría de la Placa de Carbono en el Rendimiento del Corredor.

Nombre del congreso: XII Congreso Internacional de la Asociación Española de Ciencias del Deporte.

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2023

Lugar: Madrid, España

Autores: **Ruiz-Alias, S.A.**, Pérez-Castilla, A., García-Pinillos, F.

14. Título de la aportación: ¿Podemos Predecir el Rendimiento en Carreras de Larga Distancia? Validez de Distintos Modelos Empíricos.

Nombre del congreso: XII Congreso Internacional de la Asociación Española de Ciencias del Deporte.

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2023

Lugar: Madrid, España

Autores: **Ruiz-Alias, S.A.**, Pérez-Castilla, A., García-Pinillos, F.

15. Título de la aportación: Acute Effect of Different Velocity-Based Training Protocols on 2000-meter Rowing Ergometer Performance Time.

Nombre del congreso: XII Congreso Internacional de la Asociación Española de Ciencias del Deporte.

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2023

Lugar: Madrid, España

Autores: Pérez-Castilla, A., **Ruiz-Alias, S.A.**, García-Pinillos, F.

16. Título de la aportación: Exoboot. Prototipo de Exoesqueleto Pasivo Adaptado a la Bota Militar.

Nombre del Congreso: Ejército, Empresa y Conocimiento: Una Alianza Estratégica para el Horizonte 2035.

Tipo de aportación: Póster

Ámbito: Nacional

Año: 2020

Lugar: Granada, España

Autores: Soto-Hermoso, V.M., Chicano-Gutiérrez, J.M., Ramos-Muñoz, J.L., Molina-Molina, A., Guerrero-Martínez, A., **Ruiz-Alias, S.A.**, Ruiz-Malagón, E.J.

17. Título de la aportación: Monitorización de la Frecuencia Cardíaca en Corredores: Influencia del Dispositivo Utilizado sobre los Sistemas de Cuantificación de Carga y Estrategias de Control del Esfuerzo.

Nombre del congreso: I Congreso Internacional y III Congreso Nacional de Rendimiento Deportivo, Actividad Física y Salud y Experiencias Educativas en Educación Física.

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2024

Lugar: Jaén, España

Autores: Ruiz-Alias, S. A., García-Pinillos, F., Soto-Hermoso, V.M., Ruiz-Malagón, E.J.

18. Título de la aportación: Relación entre la asimetría de masa magra de miembros superiores e inferiores en una muestra heterogénea.

Nombre del congreso: I Congreso Internacional y III Congreso Nacional de Rendimiento Deportivo, Actividad Física y Salud y Experiencias Educativas en Educación Física.

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2024

Lugar: Jaén, España

Autores: Delgado-García, G., Teresa-Mansilla, F., **Ruiz-Alias, S. A.**, Soto-Hermoso, V.M.

19. Título de la aportación: Fiabilidad del sistema RunScribe™ para determinar variables cinemáticas de la pelvis durante la marcha y la carrera a diferentes velocidades.

Nombre del congreso: I Congreso Internacional y III Congreso Nacional de Rendimiento Deportivo, Actividad Física y Salud y Experiencias Educativas en Educación Física.

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2024

Lugar: Jaén, España

Autores: Marcos-Blanco, A., **Ruiz-Alias, S.A.**, García-Pinillos, F.

20. Título de la aportación: Determinación del Umbral Funcional de Potencia a partir de pruebas más cortas y su relación con la Potencia Crítica.

Nombre del congreso: III Congreso Internacional en Ciencias de la Salud y del Deporte

Tipo de aportación: Comunicación oral

Ámbito: Internacional

Año: 2024

Lugar: Huesca, España

Autores: Jaén-Carrillo, D., García-Pinillos, F., Pérez-Castilla, A., **Ruiz-Alias, S.A.,**
Ñacupil-Andrade, A.A.

Capítulo de Libro

- 1. Título del capítulo:** Determinación de la Condición Física Cardiovascular mediante Pruebas Accesibles.

Autores del capítulo: Ruiz-Alias, S.A.

Título del libro: Manual Sobre las Últimas Tendencias Prácticas para Evaluar y Prescribir el Entrenamiento Físico-Deportivo.

Editorial: Universidad de Almería.

Año: 2024.

- 2. Título del capítulo:** Estimación de la Velocidad Crítica y la Velocidad Aeróbica Máxima a través del Modelo de Dos Puntos en Corredores.

Autores del capítulo: Ruiz-Alias, S.A.

Título del libro: Manual Sobre las Últimas Tendencias Prácticas para Evaluar y Prescribir el Entrenamiento Físico-Deportivo.

Editorial: Universidad de Almería.

Año: 2024.

- 3. Título del capítulo:** Estimación del Rendimiento de Largas Distancias a través de la Monitorización de la Potencia en Carrera.

Autores del capítulo: Ruiz-Alias, S.A.

Título del libro: Manual Sobre las Últimas Tendencias Prácticas para Evaluar y Prescribir el Entrenamiento Físico-Deportivo.

Editorial: Universidad de Almería.

Año: 2024.

Docencia Impartida

1. **Asignatura/curso:** Fundamento de los Deportes I: Atletismo

Titulación Universitaria: Grado en Ciencias de la Actividad Física y del Deporte, Universidad de Granada, Granada, España

Duración: 180 horas (18 créditos)

Fecha: 1 de Septiembre de 2020 a 1 de Marzo de 2023

2. **Asignatura/curso:** Funcionalidades del Calzado Deportivo de Carrera

Titulación Universitaria: Máster Universitario en Rendimiento Deportivo: Entrenamiento y Valoración Funcional, Universidad Europea del Atlántico, Santander, España.

Duración: 2 horas (0.2 créditos)

Fecha: 25 de Octubre de 2021

3. **Asignatura/curso:** Funcionalidades del Calzado Deportivo de Carrera

Titulación Universitaria: Máster Universitario en Rendimiento Deportivo: Entrenamiento y Valoración Funcional, Universidad Europea del Atlántico, Santander, España.

Duración: 3 horas (0.3 créditos)

Fecha: 27 de Octubre de 2022

4. **Asignatura/curso:** Funcionalidades del Calzado Deportivo de Carrera

Titulación Universitaria: Máster Universitario en Rendimiento Deportivo: Entrenamiento y Valoración Funcional, Universidad Europea del Atlántico, Santander, España.

Duración: 3 horas (0.3 créditos)

Fecha: 25 de enero de 2023

5. **Asignatura/curso:** El Corredor de Resistencia: Importancia del Calzado en su Rendimiento, Entrenamiento, y Prevención de Lesiones

Titulación Universitaria: Jornada cultural, Facultad de Ciencias de la Educación de la Universidad de Almería.

Duración: 2.5 horas (0.25 créditos)

Fecha: 17 Noviembre de 2023

6. **Asignatura/curso:** Monitorización del corredor y gestión de plataformas de entrenamiento

Titulación Universitaria: Fundamentos teóricos y prácticos para el entrenamiento del corredor popular. Instituto Andaluz del Deporte. Programa de formación continua 2024.

Duración: 5 horas (0.5 créditos)

Fecha: 03 de Junio de 2024

7. **Asignatura/curso:** Funcionalidades del calzado de carrera: Rendimiento, entrenamiento y prevención de lesiones.

Titulación Universitaria: Fundamentos teóricos y prácticos para el entrenamiento del corredor popular. Instituto Andaluz del Deporte. Programa de formación continua 2024.

Duración: 5 horas (0.5 créditos)

Fecha: 05 de Junio de 2024

8. **Asignatura/curso:** Determinación de hitos fisiológicos a través de medios de menor y mayor accesibilidad.

Titulación Universitaria: Fundamentos teóricos y prácticos para el entrenamiento del corredor popular. Instituto Andaluz del Deporte. Programa de formación continua 2024.

Duración: 2 horas (0.2 créditos)

Fecha: 05 de Junio de 2024

9. **Asignatura/curso:** Potenciación de la cinética del consumo de oxígeno para la mejora del rendimiento en el dominio severo de intensidad.

Titulación Universitaria: Fundamentos teóricos y prácticos para el entrenamiento del corredor popular. Instituto Andaluz del Deporte. Programa de formación continua 2024.

Duración: 2 horas (0.2 créditos)

Fecha: 05 de Junio de 2024

10. **Asignatura/curso:** Shoe fitting: Determinación del calzado de carrera óptimo mediante la calorimetría indirecta.

Titulación Universitaria: Fundamentos teóricos y prácticos para el entrenamiento del corredor popular. Instituto Andaluz del Deporte. Programa de formación continua 2024.

Duración: 2 horas (0.2 créditos)

Fecha: 05 de Junio de 2024

Agradecimientos

Este ciclo se cierra sin duda gracias al esfuerzo y al cariño de muchos. A cada uno de vosotros, ¡gracias de corazón!

El 16 de septiembre de 2015, Granada nos abrió sus puertas. No sé quién llevaba más ilusión, si papá y mamá, Pongo, o mi hermana y yo. Y era para estarlo, esa puerta se llevaba construyendo desde hacía años, en especial, por dos padres que antepusieron todo por sus hijos. Esta tesis supone para mí mi forma de agradecer el amor, la educación, y los valores que habéis inculcado tanto en mi hermana como en mí para que, a día de hoy, seamos dos personas completas. A los dos, gracias, Montserrat y yo os queremos. Nena, por supuesto, agradecerte a ti también todo lo que una hermana mayor puede darle al pequeño de la casa. Otra etapa más que cerramos juntos, como siempre, como lo quieren papá y mamá, bien cerquita uno del otro.

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Víctor, te estaré eternamente agradecido por esta oportunidad. Recuerdo con cariño citarnos en la facultad para ver la posibilidad de comenzar mis prácticas contigo y tu grupo. Bastó con decirte que era atleta para convencerte. Espero que el trabajo de estos 4

años esté a la altura de lo tanto que trabajas tú por nosotros. Admiro mucho la ambición que tienes en esta profesión. Nos das un gran ejemplo a todos los que te rodeamos, un abrazo grande.

Alejandro, en mis primeros meses de tesis no me esperaba tener que dedicarte un párrafo de agradecimientos, pero sin duda, sabes muy bien lo que significas para mí a día de hoy. Por proximidad temporal, conoces a la perfección lo que supone enfrentarse a la vida académica, y por ello, tu trato hacia mí siento que ha sido como al de un hermano menor. Me has guiado a la perfección, abriéndome oportunidades pero sin darme nada por hecho, para que así fuese yo quien se construyese su camino. ¡Alexis y Ainara tienen mucha suerte de tenerte! Sigamos disfrutando... un abrazo grande.

Natalia, mi compañera de viaje... ¡menudos cuatro años hemos compartido!. El tiempo pasa muy rápido y nos veo como si fuese ayer, sentados, lidiando el frío de la mañana, codo con codo peleando por nuestras profesiones (Tesis, Oposiciones...) y con nuestra pequeña alegría (Leo) ayudando a su manera. El ritmo de estos 4 años no hubiese sido sostenible sin tu ayuda. Gracias por entender mis ganas y por enseñarme a frenar cuando era necesario. Granada me guardará siempre este cachito de ti, te quiero mucho.

Esta etapa también la guardaré gratamente en la memoria gracias al cariño recibido por toda la comunidad universitaria que nos rodea en esto de las Ciencias del Deporte desde Granada (Emilio, Alejandro, Chicano, Iván), Zaragoza (Luis Enrique, Diego) y Almería (Manolo). Mil gracias por abrirme vuestras puertas y darme la oportunidad de seguir creciendo.

Anexos

Propuesta de evaluación del calzado de competición

En base a la evidencia recogida mediante la presente Tesis Doctoral, se establece una propuesta de evaluación del calzado de competición con la finalidad de integrar una categorización de todos los elementos que contribuyen a la mejora del rendimiento (i.e., peso, resiliencia de la media suela, rigidez longitudinal, efecto balancín):

1. El peso del calzado

Método de evaluación: Báscula de precisión



Categorización:

Categoría	Peso (gramos)
0	400
1	350
2	300
3	250
4	200
5	150

Consulta:

El peso del calzado de los modelos actuales de competición puede ser consultado en <https://runrepeat.com/>.

2. Resiliencia de la media suela

Método de evaluación: Test masa de caída



Mediante un tubo con transparencia posicionado en el retropié del calzado, dejar caer una esfera de plomo y medir la diferencia de altura tras el primer contacto respecto a la altura inicial.

Categorización:

Categoría	Δ altura inicial (%)
0	10
1	20
2	30
3	40
4	50
5	60

3. Rigidez longitudinal

Método de evaluación: Dinamómetro digital



Anclar el calzado y con el dinamómetro posicionado en el retropié, recrear la fase de propulsión.

Categorización:

Categoría	Fuerza (N)
0	10
1	20
2	30
3	40
4	50
5	60

Consulta:

La rigidez del calzado de los modelos actuales de competición puede ser consultado en <https://runrepeat.com/>.

4. Efecto balancín

Método de evaluación: Dinamómetro + Observacional



Tras evaluar la rigidez del calzado, determinar la posición del eje de rotación respecto a la articulación metatarsofalángica.

Categorización:

Categoría	Rigidez (Categoría)	Posición eje rotación (Respecto a MTP)
0	0	--
1	1-3	Posterior a MTP
2	1-3	En o anterior a MTP
3	4-5	Posterior a MTP
4	4-5	En MTP
5	4-5	Anterior a MTP

5. Índice de rendimiento del calzado

Item	Escala	Factor de corrección
Peso	_/5	1
Resiliencia media suela	_/5	1
Rigidez longitudinal	_/5	1
Efecto balancín	_/5	3
Total (%) = $(\sum [\text{Escala} * \text{Factor de corrección}]/120) * 100$		

Ejemplo de evaluación:

Item	Evaluación		Escala	
	NVP3	ANB4	NVP3	ANB4
Peso	190	260	3/5	2/5
Resiliencia media suela	63	60	5/5	5/5
Rigidez longitudinal	55.8	25.2	4/5	1/5
Efecto balancín	En MTP	En MTP	4/5	2/5
Índice			90%	47%

NVP3: Nike Varpofly 3; ANB4: Asics Novablast 4

Consentimiento informado del participante

CONSENTIMIENTO INFORMADO DEL PARTICIPANTE (EN SU CASO, PADRE/MADRE/TUTOR)

(Los artículos se refieren a la Ley de Investigación Biomédica, BOE 4 de julio de 2007)

D./Dña
con D.N.I. nº..... y fecha de nacimiento/...../.....

Declaro que:

1. He leído (o me han leído) la hoja de información al paciente del proyecto: Análisis Biomecánico y Fisiológico de la Influencia del Calzado Deportivo en el Rendimiento del Corredor

2. He comprendido la investigación que se va a realizar con mi participación y he tenido la oportunidad de resolver cualquier duda al respecto.

3. Así mismo, se me ha informado de que:

- Se hace constar que el participante manifiesta expresamente decir la verdad en sus respuestas para garantizar los datos reales sobre su estado físico o salud o los que se le solicitan (art. 23.1. L.I.B.).
- Tengo derecho a no otorgar mi consentimiento a participar y a revocarlo en cualquier momento del estudio (art. 4.3. L.I.B.).
- La falta de consentimiento a iniciar el estudio o su revocación una vez iniciado no me supondrá perjuicio alguno (en cualquier otro derecho) o discriminación (art. 4.4 y 6. L.I.B.).
- Seré informado, si así lo deseo, de los datos que se obtengan durante la investigación (art. 4.5 y 27.2. L.I.B.) y de la forma de obtener dicha información (art. 15.2. L.I.B.).
- Tengo derecho a decidir que no se me comuniquen los datos de la investigación (con las excepciones legales pertinentes) (art. 4.5. L.I.B.).
- Los datos que se obtengan con mi participación en la investigación son anónimos y si al publicarlos hay que mencionar mi nombre será precisa mi autorización (art. 15.2. L.I.B.).

(Los datos recogidos en esta investigación serán anónimos y su uso se regirá por lo recogido en la legislación vigente en relación a la Protección de Datos de Carácter Personal. Los datos personales del participante serán tratados conforme a los términos establecidos en la Ley Orgánica 3/2018, de 5 de diciembre, de Protección de Datos Personales y garantía de los derechos digitales, pudiendo ejecutar en cualquier momento los derechos de acceso, rectificación, cancelación u oposición, poniéndose en contacto con el investigador principal según los datos incluidos en el documento de información al participante).

4. Acepto participar de forma voluntaria en el proyecto arriba mencionado.

Firma del participante

Lugar y fecha

Documento de información al participante

DOCUMENTO DE INFORMACIÓN AL PARTICIPANTE (EN SU CASO, PADRE/MADRE/TUTOR)

(Los artículos se refieren a la Ley de Investigación Biomédica, BOE 4 de julio de 2007)

A) DATOS OBLIGATORIOS

1. Datos del investigador responsable del proyecto (art. 15.2. L.I.B.).

1.1. Nombre y apellidos: Santiago Alejo Ruiz Alias

1.2. D.N.I: 49076535-D

1.3. Centro, teléfono, correo electrónico:

Facultad de Ciencias de la Actividad Física y del Deporte. Carretera de Alfacar s/n, 18011, Granada, España.

628923011

aljrui@ugr.es

2. Datos sobre el proyecto (art. 15.2. L.I.B.).

2.1. Título y fuente de financiación del proyecto:

Análisis Biomecánico y Fisiológico de la Influencia del Calzado Deportivo en el Rendimiento del Corredor. Proyecto de tesis financiado por el Ministerio de Ciencia, Innovación y Universidades (FPU19/00542).

2.2. Naturaleza, importancia y beneficios que se esperan en el proyecto:

El presente proyecto tiene por objetivo abordar la controversia existente sobre el dopaje tecnológico en carrera asociada al calzado deportivo. Los resultados que se obtengan permitirán aportar a la comunidad científica y deportiva, claras indicaciones sobre los beneficios que el calzado deportivo pueda aportar al rendimiento del corredor en las diversas pruebas de medio-fondo y fondo.

2.3. Las implicaciones y riesgos, si los hubiese, de la investigación que se pretende realizar:

La participación en el presente proyecto involucra el cumplimiento de 5 sesiones que consistirán en:

1º sesión (60 minutos): Determinación del nivel del participante

El desarrollo de esta sesión tiene por objetivo determinar la inclusión o exclusión del participante en el estudio en base a su nivel de condición física. Para ello, se realizará un test de intensidad incremental en tapiz rodante compuesto por palieres de 3 minutos de duración. Antes de iniciar el protocolo, se realizará una punción en el dedo índice para tomar una gota de sangre al final de cada palier. En función de la condición física del participante, este protocolo involucra completar unos 4 a 6 palieres. Dichas muestras nos permiten determinar esfuerzo que al participante le supone una determinada velocidad de carrera. Una vez finalizada la evaluación, dichas muestras serán depositadas en los recipientes de desechos específicos para tales residuos.

2º y 3º sesión (60 minutos): Análisis de la economía y biomecánica de carrera

El desarrollo de esta sesión tiene por objetivo analizar la economía y biomecánica de carrera del participante haciendo uso de distintos calzados deportivos. Para ello, se realizará un protocolo de carrera en tapiz rodante a intensidades inferiores al umbral láctico donde el participante será monitorizado con un analizador de gases y un sistema de captura de movimiento. El analizador de gases requiere el uso de una máscara facial por donde el participante respirará durante el protocolo de carrera. La máscara cuenta con filtros antivirales

y antibacterianos además de pasar tras su uso por un protocolo de desinfección. El sistema de captura de movimiento requiere de la colocación de una serie de marcadores reflectantes en la pierna del participante.

4º y 5º sesión (60 minutos): Test de rendimiento

El desarrollo de esta sesión tiene por objetivo analizar el rendimiento de carrera del participante en una distancia de 3000 metros haciendo uso de distintos calzados deportivos. Para ello, el participante correrá dos veces dicha distancia en días distintos con una recuperación de al menos 72 horas. Al participante se le solicitará completar esta distancia en el menor tiempo posible siendo este quien determine la intensidad por voluntad propia.

El desarrollo de las sesiones de evaluación carece de riesgos para la salud de los corredor.

2.4. Uso potencial de los resultados de la investigación en el futuro, incluido el comercial:

Los resultados obtenidos tendrán como fin principal aportar soluciones a la controversia existente sobre el dopaje tecnológico en carrera asociado al calzado deportivo.

3. Medidas para asegurar una compensación adecuada si sufre algún daño o molestia causada por la investigación (art. 15.2 y art. 18. L.I.B):

El proyecto de investigación carece de procedimientos invasivos que supongan un riesgo para la salud participante.

B) OTROS DATOS (incluya cualquier otra información que considere necesaria para la correcta información del participante).

La participación en este proyecto es voluntaria y no involucra una compensación económica. Los participantes podrán retirarse del estudio en cualquier momento que lo deseen sin dar más explicaciones.

Los datos personales recogidos con los fines propios de este proyecto de investigación serán seudonimizados y acordes a lo establecido en la Ley Orgánica 3/2018, de 5 de diciembre, de Protección de Datos Personales y garantía de los derechos digitales.