PHYSIOLOGICAL AND BIOMECHANICAL DETERMINANTS OF PERFORMANCE IN ELITE RACE WALKERS

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"You are going to die one day and none of this is going to matter. So, enjoy yourself. Do something positive. Project some love. Make someone happy. Laugh a little bit. Appreciate the moment. And do your work."

Naval Ravikant

Acknowledgements

And finally, the thesis is finished. I closed another stage of my life, summed in a book. However, for me, this thesis is more than a final result. This thesis resumes partially the whole picture of this long, beautiful and though journey. It has required lot of effort, passion and dedication, but now I can consider it complete. However, without the support of many-many people, all this work could not have been performed. In more ways than one, all of you have contributed to a fantastic journey.

"Believe in something, even if it means sacrificing everything".

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"Surround yourself with greatness, it is contagious".

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A good support system is required to survive in such a big project. I was very lucky to collaborate and have the support of all the staff of the Department of Physiology of the University of the Basque Country in Leioa, be it the use of the lab, working space, coffee, ideas and time. A special mention to Dr. Jon Torres-Unda and Professor Jon Irazusta, for their help and including me as part of the team during visits. I cannot finish an academic acknowledgement without saying thank you to Danielle Prins, who assisted me very patiently with biomechanical data analysis, and the other members of staff at Sports Science Institute of South Africa (Cape Town, South Africa) for hosting me during my visit.

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"The path to becoming a Doctor is littered with distractions. I would like to thank those distractions for making me the person I am."

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Nire hizkuntza kuttunari,

"Izarren hautsa egun batean bilakatu zen bizigai,
Hauts hartatikan uste gabean noizpait giûaden gu ernai.
Eta horrela bizitzen gera sortuz ta sortuz gure aukera
Atsedenik hartu gabe: lana egiûaz goaz aurrera
Kate horretan denok batera gogorki loturik gaude.

Gizonak ba du inguru latz bat menperatzeko premia,
Burruka hortan bizi da eta hori du bere egia.
Ekin ta ekin bilatzen ditu, saiatze hortan ezin gelditu,
Jakintza eta argia; bide ilunak nekez aurkitu
Lege berriak noizpait erditu, hortan jokatuz bizia.

Gizonen lana jakintza dugu: ezagutuz aldatzea,
Naturarekin bat izan eta harremanentan sartzea.
Eta indarrak ongi errotuz, gure sustraiak lurrari lotuz,
Bertatikan irautea: ezaren gudaz baietza sortuz,
Ukazioa legetzat hartuz beti aurrera joatea."

(Izarren hautsa, Xabier Lete)

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ABSTRACT

"The scientist is not a person who gives the right answers, he's one who asks the right questions."

Claude Lévi-Strauss

1. Abstract

Background: Physiological and biomechanical factors are considered key to high-level athletic success. However, the relationships between physiological and biomechanical variables with race walking performance in world-class athletes are yet to be explored.

Purpose: The core of this thesis aims to assess different factors related to elite performance, with special interest in anthropometric, physiological and biomechanical parameters.

Methods: Twenty-nine world-class race walkers (21 men & 8 women) participated in the studies included in this thesis. Anthropometric characteristics, body composition and the somatotype were measured. Bone mineral density of the calcaneus was estimated using measures of speed of sound (SOS), broadband ultrasound attenuation (BUA), stiffness index (SI), Z- and T-scores. Additionally, participants completed an incremental race walking test where race walking economy ($ml \cdot kg^{-1} \cdot km^{-1}$) and spatiotemporal gait variables were analysed at different speeds. Moreover, kinematic, ground reaction forces and muscle activity data during the gait were collected during over ground walking trials at 12 and 14 $km \cdot h^{-1}$.

Results: (1) Mean height, body mass and body mass index were 177.1 ± 7.1 cm, 66.4 ± 5.8 kg, and 21.2 ± 1.3 $kg \cdot m^2$ for men and 165.6 ± 4.5 cm, 53.6 ± 3.7 kg, and 19.6 ± 1.6 $kg \cdot m^2$ for women, respectively. Women presented greater body fat content (6.7 ± 0.6 vs. 12.2 ± 0.8%; very large effect), less muscle mass (65.6 ± 4.6 *vs.* 61.6 ± 2.6 kg; large effect) and were more endomorphic (large effect) than men. Men specialists in 20-km showed greater muscle mass (66.7 ± 4.9 *vs.* 64.4 ± 4.3 kg; moderate effect), and slightly higher skinfolds, girths, body fat content and were more mesomorphic than 50-km specialists (moderate effect).

(2) The 20-km race walkers presented significantly higher SOS and SI ($p<0.05$) values than the 50-km male race walkers, who had lower mean T- and Z-scores ($p<0.01$). In addition, BUA differed between male and female 20-km race walkers ($p=0.049$). Greater training load and the initial loading rate were associated with BUA ($p<0.05$).

Greater time spent in ground contact and propulsive phase, were associated with higher SOS and SI (p<0.05).

(3) 20-km race walking performance was related to race walking economy, being the fastest race walkers those displaying reduced oxygen cost at a given speed (r=0.760, p<0.001). Longer ground contact times, shorter flight times, longer midstance sub-phase and shorter propulsive sub-phase during stance were related to a better race walking economy (p<0.05; moderate effect).

(4) When compared to runners running at similar speeds, race walkers exhibited longer contact and swing times, shorter strides and higher cadences (p<0.001). Race walkers also had lower hip flexion-extension (p=0.011), greater knee extension (p=0.001) and reduced peak dorsi-plantarflexion during stance (p=0.001). Smaller ranges of frontal plane motion were observed in race walkers in both the knee and ankle (p<0.01), and greater hip adduction-abduction (p=0.018) and ankle rotation (p=0.004) were found in race walkers. Runners exhibited greater hip and knee flexion moments, and lower ankle flexion during 24-40% of the gait cycle.

(5) More economical race walkers exhibit greater activation of the *gluteus maximus* (r=0.716, p=0.022), *biceps femoris* (r=0.801, p=0.011) and *medial gastrocnemius* (r=0.662, p=0.041) prior to initial contact and the weight acceptance sub-phase. Additionally, during the propulsive phase and the early swing phase, race walkers with higher activation of the *rectus femoris* (r=0.798, p=0.021) showed better economy.

Conclusions: The present study expands the limited knowledge on the anthropometric and bone characteristics of elite top-class race walkers, providing coaches a reference values to control the training development of the race walker. Due to the rules that governs the event, the gait pattern differences between running and race walking may be due to a specific motor control. Race walkers must optimise a peculiar gait pattern to excel, especially taking into account that the more economical race walkers are the fastest ones. Finally, race walkers have to optimise neuromuscular control and muscle action to achieve efficient energy transfer. These findings may give new insights for race walking coaching, with regards to the development of specific training strategies that take into account the special biomechanical and physiological demands of the sport.

2

CONTRIBUTIONS

''Life is like riding a bicycle. To keep your balance, you must keep moving.''

Albert Einstein

2. Candidates contributions

2.1 Scientific articles

Study 0: Published. Gomez-Ezeiza, J., Granados, C., & Santos-Concejero, J. (2016). Different competition approaches in a world-class 50-km racewalker during an Olympic year. The Journal of Sports Medicine and Physical Fitness, 56(11), 1423-1427.

Quality Indicators: ISI-JCR Impact factor: 1,120. 65/81 SPORT SCIENCES 2017

ISSN: 0022-4707.

Study 1: Published. Gomez-Ezeiza, J., Tam, N., Torres-Unda, J., Granados, C., & Santos-Concejero, J. (2018). Anthropometric characteristics of top-class Olympic racewalkers. The Journal of Sports Medicine and Physical Fitness. [Epub ahead of print].

Quality Indicators: ISI-JCR Impact factor: 1,120. 65/81 SPORT SCIENCES 2017

ISSN: 0022-4707.

Study 2: Under review. Gomez-Ezeiza, J., Torres-Unda, J., Tam, N., Irazusta, J., Granados, C., & Santos-Concejero, J. (2018). The influence of racewalking on the calcaneal bone density status in world-class racewalkers. Journal of Sport and Health Science.

Quality Indicators: ISI-JCR Impact factor: 1,215. 60/82 SPORT SCIENCES 2016. ISSN 0022-4707.

Study 3: Published. Gomez-Ezeiza, J., Tam, N., Torres-Unda, J., Granados, C., & Santos-Concejero, J. (2018). Racewalking gait and its influence on racewalking economy in World-Class racewalkers. Journal of Sports Sciences. [Epub ahead of print].

Quality Indicators: ISI-JCR Impact factor: 2,733. 19/81 SPORT SCIENCES 2017

ISSN: 0264-0414.

Study 4: Under review. Gomez-Ezeiza, J., Hanley, B., Lascurain, I., Tam, N., & Santos-Concejero, J. (2018). Biomechanical analysis of gait waveform data in elite race walkers and runners. Gait & Posture.

Quality Indicators: ISI-JCR Impact factor: 2,733. 19/81 SPORT SCIENCES 2017

ISSN: 0264-0414.

Study 5: Published. Gomez-Ezeiza, J., Santos-Concejero, J., Torres-Unda J., Hanley, B., Tam, N. (2019). Muscle activation patterns correlate with race walking economy in elite race walkers: a waveform analysis. International Journal of Sports Physiology and Performance. [Epub ahead of print].

Quality Indicators: ISI-JCR Impact factor: 3,384 10/81 SPORT SCIENCES 2017

ISSN: 1555-0265.

2.2 Scientific congresses and seminars

Invited presentation. “Estrategias para Doha 2019, equipo nacional de marcha”. Concentracion nacional del equipo nacional. Leon, Spain, 2018. Vitoria-Gasteiz, Spain, 2018.

Invited presentation. “Análisis de la marcha, ¿qué pruebas de control tenemos?”. Testing, como valorar en el deporte (V. Jornadas de actualizacion en rendimiento Deportivo). Vitoria-Gasteiz, Spain, 2018.

Oral presentation. “Biomechanical analysis of gait waveform data: racewalking vs Kenyan runners”. 23rd Annual Congress of the European College of Sport Science. Dublin, Ireland, 2018.

Invited presentation. “La economía de la marcha como factor determinante del rendimiento”. Seminario Internacional de Marcha Atletica. Guadix, España, 2017.

Oral presentation. “Anthropometric characteristics of world-class racewalkers”. 2nd Sports Science & Fitness Congress. Cologne, Germany, 2017.

Oral presentation. “Factors related to calcaneal bone density in world-class racewalkers”. 22nd Annual Congress of the European College of Sport Science. Essen, Germany 2017.

Oral presentation. “Physiological and biomechanical determinants of performance in world-class racewalkers”. 22nd Annual Congress of the European College of Sport Science. Essen, Germany 2017.

Invited presentation. “Primeros resultados de los factores biomecánicos y fisiológicos de marchadores de élite”. Seminario Marcha Real Federación Española de Atletismo. Benicassim, España, 2016.

Oral presentation. “Análisis del ciclo de paso de marchadores de clase mundial y su influencia en la economía de la marcha”. XVI Congreso de la Sociedad Española de Medicina del Deporte. Granada, España 2016

Poster presentation. “La influencia de la marcha atlética en la rigidez del calcáneo en marchadores de élite”. XVI Congreso de la Sociedad Española de Medicina del Deporte. Granada, España 2016

2.3 Books and Book chapters

Book edition: Writing. *The 21st Century Racewalking: Science and practice*. IAAF, 2018.

Book chapter: Under review. *The 21st Century Racewalking: Science and practice*. IAAF, 2018.

2.4 International experience and collaboration with institutions

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Australian Institute of Sports. Canberra, Australia.

Division of Sports and Exercise science, University of Canberra. Canberra, Australia.

Aspetar. Doha, Qatar.

Japan Institute of Sports Science. Tokyo, Japan.

Division of Sports Biomechanics, KIHU Research Institute for Olympic Sports. Jyväskylä, Finland.

Department of Exercise Physiology, Brazil Olympic Committee. Rio de Janeiro, Brazil.

ALTIS, elite athletes training centre. Phoenix, USA.

High performance Institute, North-West University. Potchefstroom, South Africa.

3

BACKGROUND

"Today a reader, tomorrow a leader."

Margaret Fuller

3. Theoretical background

Competitive race walking arose from the increased popularity of long-distance walking events during the 18th and 19th century England, also known as pedestrianism (Kozloff, 2004). Interestingly, this was often as a result of a wager between individuals. This often attracted spectatorship and became a fixture at fairs and public gatherings. Towards the end of the 19th century certain vague rules were implemented that included a “straightened leg at least once in a stride” and “fair heel and toe rule” (the toe of one foot could not leave the ground before the heel of the following foot) (Walsh, 1856).

Race walking rules further evolved over the years that culminated to its introduction to the Olympic Games of 1908 in London. Gradually, race walking was further defined with specific competitive distances and implementation of rules to maintain the essence of walking. At the first time, race walking looked like normal walking but in a faster pace. However, with the emerge of new technical features, performances and walking speed improved, replaced by the modern race walking style (Osterhoudt, 2000). To date, race walking is included at all major athletic championships, including the Olympic Games. Since 2016, the competitive distances are equal for both sexes, with the inclusion of the women’s 50 km event in addition to the 20-km men and women and 50-km men events.

Currently, according to the International Association of Athletics Federations (IAAF), racewalking is defined as (IAAF, 2016):

“A *progression of steps so taken that the walker makes contact with the ground, so that no visible (to the human eye) loss of contact occurs. The advancing leg must be straightened (i.e. not bent at the knee) from the moment of first contact with the ground until the vertical upright position*”.

Unlike running events, this definition regulates the race walking gait pattern with two specific rules. Firstly, race walkers should not exhibit any visible loss of contact with the ground. Secondly, race walkers must maintain a straightened knee from the initial contact with the ground until the body centre of mass (CM) passes over the foot (vertical upright position) (Hanley, Bissas, & Drake, 2013).

These restrictions in gait are monitored and enforced by official-accredited judges. Their purpose is to ensure that race walkers comply with the rules during competition and to warn or inform athletes when the rule is violated. Disqualifying warnings by three different judges, placed alongside the race course, are required to disqualify the athlete from the competition (IAAF, 2016). Thus, it is imperative that the athlete's ability to maintain a gait pattern that adheres to the rules is essential to race walking success (Hanley, 2012).

Despite the rules that restrict the athlete´s body to comply with the race walking event, race walkers are able to ambulate faster than the typical recreational runner (Lara et al., 2016). In fact, the current world record of the senior men´s 20-km is 1 hour 16min 36sec that equates to 15.66 $km \cdot h^{-1}$ (3:49 $min \cdot km^{-1}$). Whereas, the women's record is 1 hour 24min 38sec with an average speed of 14.18 $km \cdot h^{-1}$ (4:13 $min \cdot km^{-1}$). While 50-km racewalking world records are set at 3hour 32min 33sec for men (14.11 $km \cdot h^{-1}$; 4:15 $min \cdot km^{-1}$) and 4hour 05min 56sec for women (12.19 $km \cdot h^{-1}$; 4.55 $min \cdot km^{-1}$) (as of the 21/09/2018). These results are achieved through the ability to adapt and evolve the normal walking gait pattern to the current modern race walking style (Osterhoudt, 2000). This gait pattern requires technical mastery to compete at the highest level (Cazzola, Pavei, & Preatoni, 2016). Thus, success in race walking will require a great physical endurance capacity (Hilliard, 1986), as well as a highly standard technical ability (Padulo et al., 2013).

These great capacities are linked to specific factors that can affect race walking performance. However, thee question then arises as to which those factors are. Traditionally, these factors where based on physiological performance factors. However, at the last decade, the biomechanical factors, linked mainly to movement optimisation, have been attributed to a number of performance factors. Additionally, optimisation of the movement was also linked to anthropometrical factors.

3.1 Physiological markers of performance

Success in this kind of endurance event has traditionally been mostly been attributed to a number of physiological factors, including a 1) high cardiac output; 2) high capacity to uptake and delivery oxygen to active muscles; and 3) high lactate threshold (Nummela, Keränen, & Mikkelsson, 2007).

It is well known that the basic physiological attribute to perform in endurance events is the level of aerobic metabolism that the athlete can maintain during a race (Coyle et al., 1991). The upper limit of this metabolism is called 'maximal oxygen uptake' or VO_{2max} and constitutes one of the most used variables to evaluate the cardiorespiratory capacity of the athlete (Noakes, 2000). Bassett & Howley (2000) defined the VO_{2max} as the highest rate at which oxygen can be absorbed and used by the muscles. The diffusion of the air oxygen to the mitochondria involves a series of steps: 1) the pulmonary diffusion, 2) the cardiac output, 3) the oxygen transport in the blood and 4) the oxygen consumption in the muscle.

The cardiovascular demands of endurance events are usually very high, and several studies have reported VO_{2max} than range from 75-80 $ml \cdot min^{-1} \cdot kg^{-1}$ in well-trained endurance athletes (Nevill et al., 2003). These high VO_{2max} values can be attributed mostly to training and the genetic background of the athlete. Training can induce different adaptations, such as: increased cardiac stroke volume, increased blood volume, increased capillary density and mitochondrial density and efficiency (Saltin et al., 1976). However, an exceptional genetic background can also be a critical factor, determining the initial VO_{2max} value in the childhood, as well as the trainability of this variable for the athlete (Bouchard, 2012).

Despite these maximal values, endurance events are performed at an average pace below the maximal oxygen consumption, failing to be the best endurance predictable attribute (Noakes, 2000). Despite maximal oxygen uptake values lower than 70 $ml \cdot min^{-1} \cdot kg^{-1}$ have been documented in elite athletes (Boileau, Mayhew, Riner, & Lussier, 1982), it would be unlikely to achieve world-class endurance performances with these low values (Foster & Lucia, 2007).

Although the maximal aerobic capacity has been widely studied as a determinant of endurance performance, the importance of a new physiological attribute grew up in the last decade, the oxygen cost of transport. This oxygen cost of transport is defined as the steady-state oxygen consumption (VO_2) at a given submaximal velocity and it referred to as economy or movement efficiency (Barnes & Kilding, 2015). The importance of the movement efficiency was strengthened when Foster and Lucia (Foster & Lucia, 2007) found that in well-trained homogenous groups of athletes, the oxygen cost of transport was the most appropriate variable to discriminate between elite performers. This idea has lately been supported by several studies that identified the oxygen cost of transport as a critical factor contributing to performance in endurance sports including running (Santos-Concejero et al., 2015), cycling (Faria, Parker, & Faria, 2005), swimming (Toussaint, Knops, De Groot, & Hollander, 1990) or cross-country skiing (Sandbakk & Holmberg, 2013).

A favourable movement efficiency is the result of a complex interaction of various factors that lead to efficient muscle work and a fast and effective movement (Saunders, Pyne, Telford, & Hawley, 2004). However, the oxygen cost at a given distance can vary near 30-40% among individuals (Joyner, 1991). Inter-individual oxygen cost variations have been attributed to different metabolic and physiological factors (Barnes & Kilding, 2015), neuromuscular factors (Tam, Tucker, Santos-Concejero, Prins, & Lamberts, 2018), anthropometric factors (Bergh, Sjodin, Forsberg, & Svedenhag, 1991) and to biomechanical variables (Chapman et al., 2012). Although some athletes are predisposed to have a good oxygen cost of transport (Bouchard, 2012; Tucker, Santos-Concejero, & Collins, 2013), positive response and adaptations can occur as a consequence of specific training and technical strategies (Balsalobre-Fernández, Santos-Concejero, & Grivas, 2016; Beneke & Hutler, 2005; Kenneally, Casado, & Santos-Concejero, 2017).

3.2 Anthropometric factors

Numerous studies have found relationships between endurance performance and anthropometrical parameters, based on the proportional relationships between metabolic cost and body mass (Kram & Taylor, 1990). The most important physiological metrics to excel in endurance events are dependent on body mass (i.e. VO_{2max} in $ml \cdot min^{-1} \cdot kg^{-1}$, running economy in $ml \cdot min^{-1} \cdot km^{-1}$) (Stellingwerff, 2018). Thus, the body composition is known to influence an athlete's potential within a sport such as running (Knechtle, 2014), cycling (Basset, Billaut, & Joanisse, 2014) and skiing (Carlsson, Carlsson, Hammarström, Malm, & Tonkonogi, 2014). For instance, Teunissen et al. (2007) showed that the 74% of the total metabolic cost of running is generated by the support of the body weight.

As race walking is an endurance event based on the forward propulsion of the body, a reduced body mass might be a good strategy to improve performance (Stellingwerff, 2018). However, too low body mass may be a consequence of muscle mass loss (Heydenreich, Kayser, Schutz, & Melzer, 2017), low bone mineral density (Tam, Santos-Concejero, Tucker, Lamberts, & Micklesfield, 2017), sickness (Gleeson, 2006) and injury (Tam et al., 2017), which would ultimately affect performance outcomes by decreasing the ability to enhance training adaptations and to generate optimal power and speed (Stellingwerff, 2018).

Race walkers may improve their anthropometrical profile as a strategy to ensure health, generate positive training adaptations and perform in the best conditions, Many endurance athletes use different nutritional strategies to optimise their body composition (Martinsen, Bratland-Sanda, Eriksson, & Sundgot-Borgen, 2010) and specific training regimes have also been reported to induce specific functional and structural adaptations, including changes in anthropometrical variables such as body mass and the sum of skinfolds (Knechtle, 2014). Elite race walking training regimes are typically characterised by high training volumes at low and moderate intensities, which may result in certain specific functional and structural adaptations (Gomez-Ezeiza, Granados, & Santos-Concejero, 2016). Although some studies have previously reported that well-trained race walkers have similar anthropometric characteristics to other endurance athletes (Hagberg & Coyle, 1984), the anthropometrical profiles of elite race walkers of different distances are yet to be explored.

Bone mineral density (BMD)

While the body composition profile is, in fact, known to play an important role in determining an athlete's potential within a sport, the situation and evolution of elite race walkers' bone mineral density is unknown. It has been reported that elite race walkers can walk up to 1000 minutes each week during the athletic season (Gomez-Ezeiza et al., 2016), which may dramatically affect the skeletal system through repetitive loading (Hetland, Haarbo, & Christiansen, 1993). Bone stimulation derived from high muscular forces and high impact forces has been reported to promote osteogenesis (Schinkel-Ivy, Burkhart, & Andrews, 2013) and the greater the forces, the greater the osteogenesis effect (Lara et al., 2016). It is known that sports linked to direct actions of gravitational forces, such as running, generate higher osteogenesis than sports like swimming or rowing (Tenforde & Fredericson, 2011). Similarly, animal studies using external loads have found higher bone osteogenesis by applying high magnitude strains at a high rate and relatively lower strain cycle (Rubin & Lanyon, 1984). However, there is no agreement linking bone mineral density (BMD) to training volume as some studies have found increased BMD in bones associated with impact loading (Tam et al., 2017), whereas other studies associated an increased training volume and running distances with lower bone densities (Hind, Truscott, & Evans, 2006).

Thus, it appears that the site of loading will likely influence bone density most proximal to load application. Despite this, many factors also have the potential to negatively affect bone density in athletes with high training volumes: low calcium and D vitamin intake (Tenforde, Sayres, Sainani, & Fredericson, 2010), energy deficit (Lombardi, Sanchis-Gomar, Perego, Sansoni, & Banfi, 2015), low body fat (Hetland et al., 1993) and low testosterone levels (Bennell et al., 1997). In fact, even elite runners have been found to present with low lumbar spine bone density values due to low energy availability (Tam et al., 2017) and even stress fracture (Pollock & Hamilton, 2008). This suggests a risk in elite race walkers who are exposed to both high training loads and constrained gait patterns and loading.

Bone health has been extensively assessed in sedentary populations determining bone formation and turnover (Babatunde & Forsyth, 2013). Similarly, a few studies on bone health in elite athletes have also been published across various sporting disciplines (Tenforde & Fredericson, 2011), including skiers (Pettersson, Alfredson, Nordström, Henriksson-Larsén, & Lorentzon, 2000), football players (Lozano-Berges et al., 2018) and endurance runners (Hind et al., 2006; Tam et al., 2017). These studies associated BMD with injuries (Khaw et al., 2004), training volumes (Hetland et al., 1993), sex or age (Wilks et al., 2009). To date, only two studies assessing bone characteristics in master race walkers have been conducted (Wilks et al., 2009), although bone characteristics in elite race walkers have yet to be explored.

Recently, Lara et al. (2016) reported calcaneal bone stiffness, a cost effective and portable method of determining bone density, in a cohort of amateur recreational runners. They found that calcaneal stiffness was higher in the endurance runners than sedentary controls. In addition, greater bone stiffness values were observed in marathon runners than their half-marathon and shorter 10-km counterparts. On the contrary, Gast et al. (2013) found an inverse association between competitive distance with BMD in short-, middle- and long-distance masters athletes. Whether or not this is exhibited in younger elite race walkers is of interest as their training volume and unique gait pattern may expose the body to different external and internal loads (Gomez-Ezeiza et al., 2016) and subsequent influence on bone density than runners. Calcaneal bone stiffness is of interest as it is the first bone exposed to the external ground reaction force at ground contact, and is also influenced by internal loading produced by the contractions of the gastrocnemius and tibialis anterior (Stabley, Moningka, Behnke, & Delp, 2014). The question arises whether any relationship between bone density, competitive distance, training volume, sex and biomechanics exist in elite race walkers. Subsequently, assessing the bone density of elite race walkers will improve our understanding of race walking's relationship with health, injury risk and performance.

3.3 Biomechanical parameters of racewalking

Race walking possesses a unique locomotor strategy different from running because of the limitations arising from Rule 230.2 set by the International Association of Athletic Federations (IAAF, 2016). Race walkers are restricted from exhibiting any visible loss of ground contact and are obliged to maintain a straightened knee from initial contact until the vertical upright position. By contrast, the absence of biomechanical restrictions on running gait allows runners to adopt their most efficient gait pattern. Despite this restriction, athletes participating in this athletic discipline reach high speeds (e.g., 15 $km \cdot h^{-1}$) through biomechanical modification of their gait (Preatoni, Ferrario, Donà, Hamill, & Rodano, 2010).

A comprehensive understanding of gait waveforms, whether kinetic or kinematic, during running and race walking in elite athletes provide insight into the specific and well-defined demands of these different gait disciplines. Pavei, Cazzola, La Torre, & Minetti (2014) concluded in a review that race walking was more efficient than normal walking at fast speeds because of the use of hip extensor and ankle plantarflexor moments to accelerate the body centre of mass, adopted to enable high speed walking in response to the rules imposed. Similarly, some studies have analysed distance running and race walking technique to understand better kinematics, motor variability and learning (Cronin, Hanley, & Bissas, 2016; Marchetti, Cappozzo, Figura, & Felici, 1982;

Preatoni et al., 2013). Nonetheless, race walking is more metabolically demanding than running as a result of the restrained biomechanics and neuromuscular coordination (Marchetti et al., 1982). Previous research suggested that race walkers enhance movement efficiency using specific gait pattern strategies (Hanley & Bissas, 2016). This was also confirmed by some researchers where shorter ground contact times, with shorter initial loading sub-phases, were associated with better oxygen cost of transport in elite race walkers (Gomez-Ezeiza et al., 2018).

Previously, joint kinematics and kinetics of race walking have been described using two-dimensional videography (Hanley & Bissas, 2013; Hanley et al., 2013) and three-dimensional motion capture (Pavei & La Torre, 2014). To date, analysis of running and race walking gait patterns are often restricted to data extraction at discrete loci such as peaks, means and ranges of motion (Williams, Snow, & Agruss, 1991).

Three-dimensional waveform comparisons of kinematics between athletic disciplines have not been conducted extensively. This has only been compared within race walking populations, whereas elite race walkers and runners have not been compared to understand and describe optimal gait patterns. Although race walking biomechanics has been explored with some degree of complex consideration such as motor variability (Preatoni et al., 2010) and functional data analysis (Cazzola et al., 2016; Donà, Preatoni, Cobelli, Rodano, & Harrison, 2009; Pavei & Torre, 2016), the full extent of gait waveform data of elite athletes has yet to be fully described in all three anatomical planes with a sufficient sample size.

Muscle activation

Although recent gait analyses in race walking have mostly assessed peaks, range of motion and other discrete parameters of the entire gait cycle (Gomez-Ezeiza et al., 2018; Hanley et al., 2013; Hoga-Miura, Ae, Fujii, & Yokozawa, 2015), a comprehensive understanding of the role and activity of the major muscles used throughout specific gait phases have not be conducted and could provide useful information. In addition, older electromyography studies assessed race walking before the implementation of modern race walking rules in 1995 (Murray, Guten, Mollinger, & Gardner, 1983) and more recent studies have analysed muscle moments, power and work through inverse dynamics (Hanley & Bissas, 2013; Hoga, Ae, Enomoto, & Fujii, 2003; Hoga et al., 2006). These estimations established the role of particular muscle group contribution to the race walking movement, suggesting the importance of smaller deceleration phases during braking in early stance and subsequent smaller acceleration phases during late stance (Hanley & Bissas, 2016). Assessing joint kinetics in elite men and women race walkers have provided novel insight of the role of specific lower limb muscles (Hanley & Bissas, 2013). From a physiological perspective, assessing muscle activity may expand and improve the validity of modelled joint kinetic data, that may further reveal the role of neuromuscular factors on race walking locomotion. Previous measurements of muscle activity on race walking have been used to support kinematic findings (Hanley & Bissas, 2013), and determine muscle contributions race walking at different gradients (Padulo et al., 2013). However, the relationship between muscle activity and oxygen cost is required to fully understand the efficiency of the locomotion used in elite race walking.

In running, imbalanced antagonist:agonist co-activation ratios have been linked with an increased energy cost of transport (Kyröläinen, Belli, & Komi, 2001), and previous research modelled lower limb muscle energy costs, using electromyography, were found to be higher in race walking than in running (Cronin, Hanley, & Bissas, 2016). However, the key factor that might facilitate a more efficient oxygen cost of transport is the timing of muscle activation during the gait cycle (Tam et al., 2016), as pre-activation of lower limb posterior musculature has been found to relate to better running economy (Heise, Morgan, Hough, & Craib, 1996; Tam, Tucker, Santos-Concejero, Prins, & Lamberts, 2018). This implicates the lower limb musculature in ground reaction force attenuation during braking at initial ground contact, this is achieved through optimising joint stiffness for a more efficient transfer of energy (Boyer & Nigg, 2004). Whether this neural preparation is also important in race walking has not been established, but is possibly crucial for athletes in this discipline given the high energy costs of race walking and restricted joint biomechanics compared with running (Cronin, Hanley, & Bissas, 2016).

Understanding the influence of muscle activation on oxygen cost of transport in race walkers is of interest as it provides insight into regulation of race walking kinematics that are associated with metabolic efficiency a marker of performance (Gomez-Ezeiza et al., 2018). Additionally, this analysis may give new insights in coaching race walkers, with regard to the development of specific training strategies that consider the specific biomechanical and physiological demands of race walking.

4

PURPOSE

"Somewhere, something incredible is waiting to be known."

Carl Sagan

4. Purpose and prospects of the research

The main aim of this doctoral dissertation was to analyse and compare the key physiological and biomechanical determinants of performance in world-class race walkers. Due to the large technical and physiological variables related to performance in elite race walking, this thesis defined specific objectives for each variable:

1. To analyse the anthropometrical characteristics of elite race walkers, comparing the values between men and women and according to the event in which they participate. We hypothesised that the anthropometrical values would differ between men and women and also according to their distance specialisation.

2. To describe and compare bone ultrasonographic variables in elite male and female race walkers, to improve our understanding of race walking and its relationship with injury risk and performance. In addition, to assess the possible influence of spatiotemporal variables and GRF characteristics of the gait cycle on the calcaneus bone density. We hypothesised that elite race walkers as endurance event participants, would show low mineral bone densities due to the characteristics of their training regimes.

3. To measure race walking economy and its relationships with performance. In addition to analyse whether spatiotemporal characteristics of the gait cycle are related to racewalking economy. We hypothesised that the best race walkers would show the best economy values, with specific spatiotemporal characteristics to enhance their racewalking efficiency, including shorter flight times.

4. To analyse and compare the kinematics and kinetics of the gait cycle in world-class runners and race walkers using three-dimensional motion capture and force

platform data. Subsequently, using 1DSPM, a thorough description and comparison of gait patterns was assessed building on research of previous studies. It was hypothesised that race walking kinetics and kinematics in all planes would differ from running at the same speed, because of the need to maintain visible contact with the ground and a straightened knee from initial contact until the vertical upright position.

5. Understanding the influence of muscle activation on oxygen cost of transport in race walkers is of interest as it provides insight into regulation of race walking kinematics that are associated with metabolic efficiency a marker of performance. Thus, the aim of this study was to analyse the influence of muscle activation patterns on oxygen cost of transport in elite race walkers over the entire gait waveform.

5

STUDIES

“A thinker sees his own actions as experiments and questions, as attempts to find out something. Success and failure are for him answers above all”

Friedrich Nietzsche

5. Studies

The empirical work of this thesis aimed to analyse, compare and describe different aspects of elite race walking, structuring them in 5 studies. As a first approach to race walking, descriptive studies were conducted analysing the anthropometry (study 1) and bone density (study 2) of the race walkers, in order to describe the anthropometric and bone status of elite race walkers and to see whether the specific training regime may have a direct implication in their specific anthropometry and bone status.

On the other hand, the core of this thesis started with the third study, aiming to stablish evidence between race walking performance and race walking economy. With the data collected, the fourth and the fifth studies were conducted. The fourth chapter compared the kinematics of elite race walkers' and elite runners' gait patterns at set speeds. Lastly, the fifth study analysed the kinetic characteristics that would help the best race walkers to be more efficient and better performers.

5.1 Study 1: Anthropometric characteristics of top-class Olympic racewalkers

5.1.1 The aim of the study

Typical training programmes in elite racewalkers involve high training volumes at low and moderate intensities, which have been reported to induce functional and structural adaptations at an anthropometric level. Since anthropometrical variables are closely related to movement efficiency and performance in endurance events, the aim of this study was to describe and compare the anthropometric profile of world-class female and male race walkers and their respective distance specialisation (20-km and 50-km). Secondly, this study aimed to establish reference values for athlete selection, talent identification and training programme development in race walking.

5.1.2 Methods

Participants

Twenty-nine international elite race walkers from Spain, Canada, Australia, France, Mexico, Sweden, Ireland and England agreed to participate in this study. All race walkers met the Olympic Entry Standard for Games of the XXXI Olympiad taking place in Rio de Janeiro 2016 (1:24:00 for men & 1:30:00 for women in 20-km and 4:06:00 in 50-km for men). Our sample also included the current World and Olympic champions for men over both 20-km and 50-km. Participants were tested during their training stages in Europe, in preparation for target International Amateur Athletics Federations' (IAAF) Permitted Race walking meetings (i.e. XXX Gran Premio Cantones de La Coruña), were informed about all the tests and possible risks involved and provided written informed consent before testing. The Ethics Committee for Research on Human subjects of the University of the Basque Country (CEISH/GIEB) granted permission for this study (REF. 66/2015).

Data collection

Anthropometric characteristics were measured in a resting state by an accredited anthropometrist following the standardised techniques adopted by the International Society for the Advancement of Kinanthropometry (ISAK). All variables, except body mass and height, were measured on the right side of the body.

Height and body mass were measured in running shorts to the nearest 0.1 cm and 0.1 kg using a portable stadiometer (Seca, Hamburg, Germany) and digital scale (Tanita Corporation, Tokyo, Japan), respectively. Eight body skinfolds (triceps, subscapular, biceps, iliac crest, supraspinale, abdominal, front thigh and medial calf) were measured to the nearest 0.2 cm using a Harpenden skinfold caliper (British Indicators Ltd, St Albans, UK) and the sum of the eight skinfolds was calculated. Bone breadths and segmental girths were measured by a small bone sliding caliper (Rosscraft Innovations Inc, Vancouver, Canada) and a retractable measuring tape (Cooper Industries, Sparks, US), respectively. Girths were corrected at the sites where the skinfold and girth measurements coincided (upper arm, thigh and calf) using the formula proposed by Jelliffe & Jelliffe (1969). All anthropometric equipment was calibrated before the assessment period, with additional checks made against certified calibration weights and rods. Every measure was performed twice, and a third measure was taken when the difference was >5% for skinfolds or >1% for other anthropometric variables.

Body fat content was calculated as proposed by Yuhasz (1974), whereas the muscle mass was calculated according to equation proposed by Matiegka (1921). Health-Carter (1990) equations were used to estimate the somatotype, determining the relative fatness (endomorphy), musculoskeletal robustness (mesomorphy) and linearity or slenderness (ectomorphy) using a score of 0.5–2.5 for low, 3.0–5.0 moderate, 5.5–7.0 high, and ≥7.5 very high.

Statistical analysis

All values are expressed as mean ± standard deviation (SD). Statistical analyses of data were performed using the Statistical Package for the Social Sciences 21.0 software package (Armonk, NY: IBM Corp, USA). Data were screened for normality of distribution and homogeneity of variances using a Shapiro-Wilk Normality Test and a Levene's test, respectively. One-way ANOVA was used to compare anthropometrical characteristics between race walkers of different sex and event. The magnitude of differences or effect sizes (ES) were calculated according to Cohen's d (1990) and interpreted as small (>0.2 and <0.6), moderate (≥0.6 and <1.2) and large (≥1.2 and <2) according to the scale proposed by Hopkins, Marshall, Tterham & Hanin (2009). Significance for all analyses was set at $p<0.05$.

5.1.3 Results

The average 20-km race walking time of the participants was 80.79 ± 2.11 min (CV=2.6%) and 90.93 ± 2.81 min (CV=3.1%) for men and women, respectively, indicating that the sample was homogenous from a performance point of view.

All the absolute anthropometric characteristics are presented in Table 1. In men, we found no significant differences in height, body mass, fat percentage or muscle mass between 50-km and 20-km specialists. However, male 50-km race walkers were significantly older than those competing in 20-km (ES=0.86 moderate effect, p=0.01) and presented lower sum of skinfolds (ES=0.78 moderate, p=0.02).

When comparing 20-km men and women specialists, we observed significant differences in height (ES=0.77 moderate, p<0.001), body mass (ES=0.83 moderate effect, p<0.001), sum of skinfold (ES=0.89 moderate effect, p<0.001), body fat content (ES=0.97 moderate, p<0.001) and muscle mass (ES=0.84 moderate effect, p<0.001).

Table 1. Anthropometrical characteristics of elite racewalkers.

Mean ± SD	**20-km Men** (*n*=11)	**50-km Men** (*n*=10)	**20-km Women** (*n*=8)
Age (years)	24.9 ± 3.2†	28.5 ± 4.9	22.5 ± 2.8
Height (cm)	177.5 ± 5.4	176.6 ± 6.9	165.5 ± 4.4*
Mass (kg)	67.8 ± 5.5	65.0 ± 3.2	53.6 ± 3.7*
∑ 8 skinfold (mm)	49.9 ± 3.9†	45.6 ± 3.5	71.9 ± 6.9*
Body fat (%)	6.8 ± 0.2	6.4 ± 0.3	12.2 ± 0.8*
Muscle mass (kg)	38.0 ± 2.9	36.5 ± 3.3	30.8 ± 1.3*
Skinfolds (mm)			
Biceps	2.8 ± 0.3	2.8 ± 0.5	5.1 ± 2.8
Subscapular	7.2 ± 0.7	7.0 ± 1.3	7.2 ± 0.9
Triceps	5.7 ± 1.5	6.0 ± 1.7	10.7 ± 1.2
Iliac crest	7.6 ± 1.0	7.1 ± 1.0	10.8 ± 2.9
Supraspinale	6.9 ± 0.82	6.1 ± 1.4	8.7 ± 2.3
Abdominal	7.5 ± 0.9	7.0 ± 1.3	9.3 ± 2.0
Front thigh	7.7 ± 1.0	7.5 ± 2.0	12.7 ± 4.1

Medial calf	4.35 ± 0.9	4.4 ± 0.9	7.2 ± 1.3
Breadths (cm)			
Wrist	4.9 ± 0.7	4.8 ± 0.6	4.2 ± 0.6
Humerus	6.1 ± 0.6	5.9 ± 0.4	5.3 ± 0.6
Femur	8.9 ± 0.8	8.6 ± 0.9	8.0 ± 0.7
Ankle	6.10 ± 0.6	6.0 ± 0.5	5.5 ± 0.7
Girths (cm)			
Relaxed arm	28.0 ± 1.2	27.6 ± 1.8	24.5 ± 1.5
Flexed arm	29.4 ± 1.3	28.7 ± 1.6	25.3 ± 1.4
Waist	73.6 ± 2.4	73.7 ± 3.05	66.0 ± 2.7
Hip	91.3 ± 2.3	90.0 ± 4.3	87.0 ± 8.1
Mid-Thigh	48.9 ± 2.2	48.2 ± 2.3	47.4 ± 2.7
Calf	36.1 ± 1.7	35.2 ± 1.3	34.1 ± 1.7

n, number of participants; CV, coefficient of variation; ∑ 8 skinfolds: biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh and medial calf. Values are mean ± SD. Denotes significant difference on main characteristics ($p<0.05$): *20-km women *vs.* 20-km men group and †20-km men *vs.* 50-km men group.

Figure 1 depicts a graphical description of individual values and the mean of the sample of somatotype values for both male and female race walkers. Again, we found no significant differences between the somatotype classification of the three groups analysed. Even though all groups presented a balanced mesomorph-ectomorph somatotype, the figure exhibits a specific somatotype profile related to the position of the mean values for each event group. In men, 20-km race walkers presented higher mesomorphism values than 50-km race walkers, with a tendency towards more muscular physique when compared to the linearity presented by the 50-km race walkers. On the other hand, 20-km female race walkers scored higher endomorphic values than men.

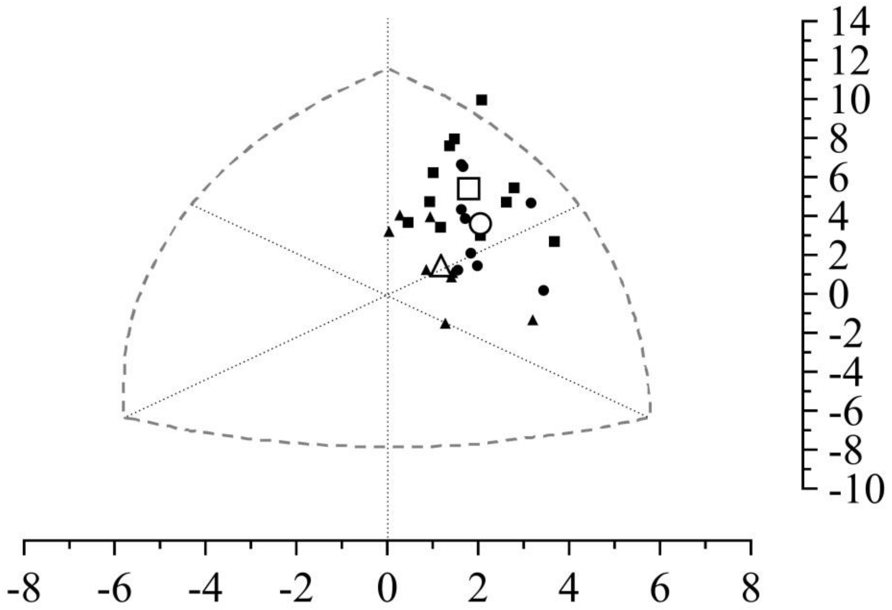

Figure 1. Somatotype distribution of elite race walkers according to sex and competitive event. Squares: 20-km male race walkers. Triangles: 20-km women race walkers. Circles: 50km male race walkers. The biggest icons represent the mean value of each event participants.

5.2 Study 2: Calcaneal bone density in world-class race walkers: biomechanical and training distance considerations.

5.2.1 The aim of the study

Calcaneal bone stiffness is of interest as it is the first bone exposed to the external ground reaction force at ground contact, and is also influenced by internal loading produced by the contractions of the gastrocnemius and tibialis anterior (Stabley, Moningka, Behnke, & Delp, 2014). The question arises whether any relationship between bone density, competitive distance, training volume, sex and biomechanics exist in elite race walkers.

Subsequently, assessing the bone density of elite race walkers will improve our understanding of race walking’s relationship with health, injury risk and performance. Thus, this study aimed to describe and compare markers of bone density in elite male and female race walkers. In addition, this study aimed to determine relationships between spatiotemporal and ground reaction variables characteristics of the gait cycle that may influence the bone density variables.

5.2.2 Methods

Participants

Twenty-four world-class race walkers (16 males and 8 females) volunteered to participate in this study. All race walkers were of Olympic Entry Standard for Rio de Janeiro 2016 (1:24:00 for men & 1:34:00 for women in 20-km and 4:06:00 in 50-km for men). Additionally, a convenience sample of sixteen (8 males and 8 females) apparently healthy male and female active students were recruited as a comparative cohort for calcaneal stiffness measures. Participants were tested during training camps in Spain, whilst they were in Europe for target IAAF Permit Race Walking meetings (i.e. XXX Gran Premio Cantones de La Coruña) before to the Rio de Janeiro 2016. Participants provided written informed consent after they were informed about all tests and possible risks involved. The Ethics Committee for Research on Human subjects of the University of the Basque Country (CEISH/GIEB) granted permission for this study (Ref.

2015/053).

Design and protocol

The study was performed in a resting state without any training or physical activity 24 hours before the measurement of the calcaneus stiffness. In addition, race walkers provided information regarding training habits and previous medical conditions and injuries. For descriptive purpose, anthropometrical characteristics were measured following the standardised techniques adopted by the International Society for the Advancement of Kinanthropometry (Stewart, Marfell-Jones, Olds, & Ridder, 2011).

Calcaneal density assessment. An ultrasonographic bone scanner (Achilles, General Electric Healthcare-Lunar, WI, USA) was used to perform an assessment of the calcaneus of the right foot (Lara et al., 2016). This scanner consisted of a control box with a heel water bath and two transducers placed opposite each other on either side of the water bath. One of these transducers emitted ultrasound signals through the water bath with the heel in it. whilst the other received the signals emitted. All signal parameters were digitised and further analysed for biological interpretation. Recent investigations have shown that quantitative ultrasound can accurately determine the exercise induced changes in bone status (Babatunde & Forsyth, 2013). The bone scanner used as found to be both valid and reliable in prior studies, with a coefficient of variation of 0.47%, 2.6% and 1.6% for speed of sound (SOS), for the broadband ultrasound attenuation (BUA) and the calcaneal stiffness index (SI), respectively (Cepollaro et al., 2014).

During this assessment race walkers were seated with their right bare foot placed in the water bath. Subsequently, expandable membranes were filled with warm water and isopropyl alcohol was used to assist coupling between the heel and the membranes, consequently eliminating air spaces. Signals recorded during each assessment by the bone scanner used to determine bone density were the speed of sound and the broadband ultrasound attenuation. While SOS assesses the elastic resistance of the bone, which is related to mineral and protein contents, the loss of ultrasound energy occurred by absorption or dispersion was assessed by the BUA, which is related to the bone density (Cepollaro et al., 2014). The calcaneal stiffness index (SI) was calculated by the combination of SOS and BUA related to participant age as follows (Lara et al., 2016):

$$SI = (0.67 \cdot BUA + 0.28 \cdot SOS) - 420$$

T- and Z-scores for calcaneus stiffness were calculated for each ultrasonographic measurement using the predetermined reference values used by the manufacturer's software. The individual T- and Z-score represents the difference between the participant's value for calcaneus stiffness and the mean value for a population of young adults of the same sex with peak bone mass and the difference between the participant's value for calcaneal stiffness and the value of a sex- and age-adjusted population, respectively (Gast et al., 2013).

Spatiotemporal variables. The spatiotemporal assessment was conducted during a treadmill test using an optical measurement system (Optojump-next, Microgate, Bolzano, Italy). The values between the 2nd and 3rd min of the race walking stage corresponding to 12 km·h^{-1} were averaged to analyse a stable gait data. Gait cycle characteristics determined were ground contact time, swing time, step length, cadence and the percentage of the stance phase at which the different sub-phases occurs (initial contact, midstance and propulsion). During stance, the initial contact sub-phase corresponds to the time from initial ground contact to foot flat; the midstance sub-phase from foot flat to initial take off and the propulsive sub-phase from initial take off to toe off.

Ground reaction forces. Ground reaction force (GRF) data were collected at 2000 Hz, using a 900 × 600 mm force platform (AMTI, Watertown, MA, USA). Race walkers completed four trials at the same speed (12 km·h^{-1}) on a 30-m indoor laboratory track. Trials were accepted if the speed was within ± 4% of target speed and when there was no visual evidence of athletes targeting the force platform. Force platform data were filtered using a low-pass fourth-order Butterworth filter with a cut-off frequency at 100 Hz. For each trial, the participants right limb was analysed. GRF data were normalized to bodyweight (BW). Peak vertical GRF as well as initial loading rate were determined as previously described by Williams, McClay, & Manal (1991).

Statistical analysis

All values are expressed as mean ± standard deviation (SD) and statistical analyses of data were performed using IBM SPSS 21 (IBM Corporation, Armok, USA). Data were screened for normality of distribution and homogeneity of variances using a Shapiro-Wilk normality test and a Levene's test respectively. A one-way analysis of covariance (ANCOVA) was employed to compare differences in bone density ultrasonographic variables between competitive event-related groups (20-km men *vs.* 50-km men *vs.* 20-km women) and control groups adjusting for age. Pearson's correlation coefficient and regression analysis were performed to assess the relationships between calcaneus bone density related ultrasonographic variables and biomechanical factors in the race walking group only. Effect sizes (ES) were interpreted as small (>0.2 and <0.6). moderate (≥0.6 and <1.2). large (≥1.2 and <2) and very large (≥2 and <4) (Hopkins, Marshall, Tterham, & Hanin, 2009). Significance was set at $p<0.05$.

5.2.3 Results

The descriptive characteristics of the race walkers and control group are listed in Table 2. Participants are considered world-class as all possessed a personal best time faster than the entry standard required to participate in the Olympic Games of Rio de Janeiro 2016 (84.0 min for men and 96.0 min for women for 20-km). The average 20-km race walking time was 81.9 ± 1.8 min, 79.8 ± 1.9 and 90.9 ± 2.8 min for 50- and 20-km male and female race walkers, respectively. Fifty-km race walkers performed higher weekly training volumes than 20-km male and female race walkers ($p<0.001$; ES=1.6, large effect & ES=2.4 very large effect, respectively). There were no significant anthropometrical differences between 50- and 20-km male race walkers, however female race walkers were shorter ($p=0.001$; ES=2.0, very large effect), lighter ($p=0.003$; ES=2.1, very large effect) and had greater sum of skinfolds ($p=0.001$; ES=4.5, very large effect) than the male race walkers. The control group were younger ($p=0.001$; ES=1.25, large effect) and had higher sum of skinfolds ($p=0.001$; ES=1.25, large effect).

Table 2. Physical and physiological characteristics of elite racewalkers (n=24) and the control group (n=24).

	50 km men (*n*=8)	**20 km men** (*n*=8)	**20 km women** (*n*=8)	**Control** (*n*=24)
Age (years)	27.4 ± 6.4	23.8 ± 3.1	22.5 ± 2.8	20.0 ± 0.2
Height (cm)	177.1 ± 6.3*	177.9 ± 8.5*	165.5 ± 4.4	173.6 ± 9.7
Mass (kg)	64.4 ± 6.1*	67.4 ± 6.2*	53.6 ± 3.7	65.8 ± 11.5
∑ 8 skinfold (mm)	45.9 ± 4.1*	46.1 ± 3.9*	71.9 ± 6.9	99.2 ± 23.3
20-km PB (min)	81.9 ± 1.8*	79.8 ± 1.9*	90.9 ± 2.8	-
Weekly Training (km)	197.5 ± 11.4*†	158.5 ± 16.5	146.8 ± 10.6	-

n, number of participants; PB, personal best; ∑ 8 skinfolds: biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh and medial calf. Values are presented as mean ± SD. * Significantly different to 20-km women ($p < 0.05$), $^{\#}$ Significantly different to race walkers ($p < 0.05$), † Significantly different to 20-km men and women ($p < 0.05$).

No differences in calcaneal ultrasonographic parameters were found between race walkers and controls regardless of adjusting for age. However, various differences were found between 50-km and 20-km men and 20-km women race walkers (Figure 2). The 20-km race walkers presented higher SOS (p=0.032; ES=1.3, large effect) and SI (p=0.041; ES=1.3, large effect) values than the 50-km male race walkers. In contrast, BUA values differed only between male and female 20-km race walkers (p=0.049; ES=1.1, moderate effect). Mean T- and Z-score were higher in the 20-km male race walkers than the 50-km male race walkers (p=0.007; ES=2.4 and p=0.003; ES=3.0, very large effect, respectively).

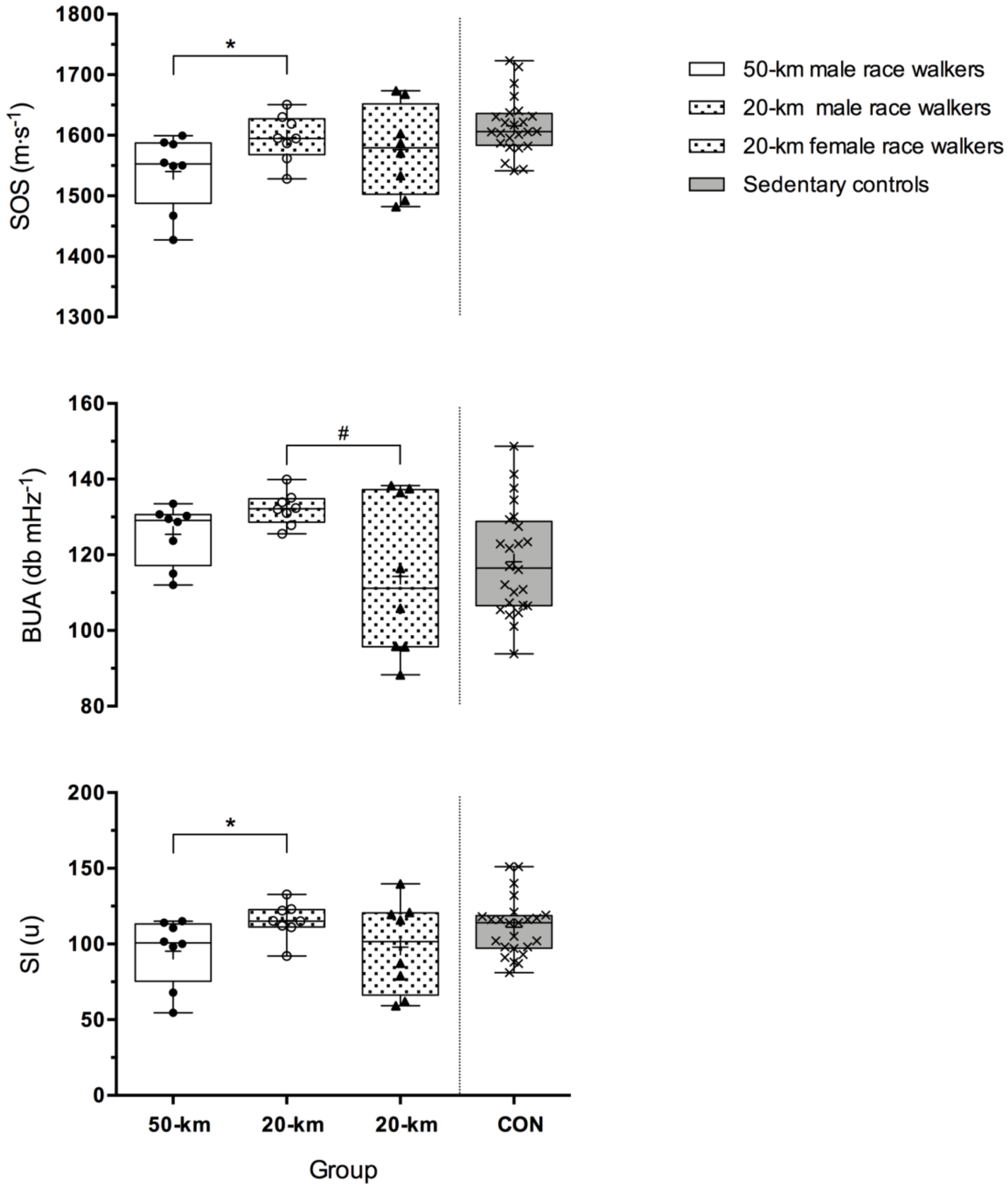

Figure 2. Ultrasonographic variables of 50-km male, 20-km male and 20-km female racewalkers and the control group. *Significantly different to 20-km male race walkers. # Significantly different to 20-km female race walkers. ($p < 0.05$).

In the race walking cohort, a greater weekly training load was associated with BUA values (r=-0.466, p=0.022). As it is described on Table 3, only initial loading rate of the ground reaction force variables was found to positively correlate with greater BUA values (r=0.442, p=0.049). Greater time spent in ground contact of the gait cycle was associated with higher SOS, BUA and SI values (r=0.696, p=0.003; r=521, p=0.039; r=0.679, p=0.004 respectively). Specifically, longer propulsive sub-phase of ground contact was related to a higher SOS (r=0.561, p=0.004) and SI values (r=0.496, p=0.014).

Table 3. Relationships between ultrasonographic variables and various biomechanical and training load variables.

	Training load (Km/week)		**Initial loading rate** (BW/s)		**Ground contact** (%)		**Propulsion sub-phase** (ground contact %)	
	r	***p***	***r***	***p***	***r***	***p***	***r***	***p***
SOS ($m \cdot s^{-1}$)		NS		NS	0.696	**0.003**	0.561	**0.004**
BUA (db mHz^{-1})	-0.466	**0.022**	0.442	**0.049**	0.521	**0.039**		NS
SI (u)		NS		NS	0.679	**0.004**	0.496	**0.014**

SOS, speed of sound; BUA, broadband ultrasound attenuation; SI, calcaneus stiffness index. r, Pearson correlation coefficient; NS, no significant differences.

5.3 Study 3: Race walking gait and its influence on race walking economy in World-Class race walkers

5.3.1 The aim of the study

Despite all previous research analysing the influence of biomechanical factors in race walking performance and economy (Morgan & Martin, 1986), the relationships between biomechanical gait variables and race walking economy in world-class race walkers a yet to be explored. Thus, the aim of this study was to analyse whether spatiotemporal characteristics of the gait cycle, including ground contact and flight times, step length, cadence and the distribution of the different sub-phases during stance (initial contact, midstance and propulsion) are related to race walking economy in world-class Olympic race walkers.

5.3.2 Methods

Participants

Twenty-one world-class Olympic male race walkers from Spain, Sweden, Ireland, Australia and Canada agreed to participate in this study. All race walkers possessed the Olympic Entry Standard for Rio de Janeiro 2016 (1:24:00 in 20 km and 4:06:00 in 50 km for men) and the sample included current 20 km world champion and other World and Olympic medallists. Participants were tested during training camps in Spain, whilst they were in Europe for target IAAF Permit Race Walking meetings (i.e. Gran Premio Cantones de A Coruña). The race walkers were informed about all tests and possible risks involved and provided written informed consent before testing. The Ethics Committee for Research on Human subjects of the University of the Basque Country granted permission for this study (CEISH 66/2015).

Design and protocols

Twenty-four hours before testing, race walkers were required to abstain from a hard training session and competition to be well rested. They were also requested to maintain their pre-competition diets throughout the test procedures and to abstain from caffeine and alcohol intake the day before testing. All testing sessions were performed under similar environmental conditions (20-23 ºC and at 09:00 - 13:00).

Anthropometry.

Anthropometrical characteristics were measured at rest by an accredited anthropometrist following the standardised techniques adopted by the *International Society for the Advancement of Kinanthropometry (ISAK)*. Height and body mass were measured in running shorts to the nearest 0.1 cm and 0.1 kg using a portable stadiometer (Seca, Hamburg, Germany) and digital scale (Tanita Corporation, Tokyo, Japan), respectively. Eight body skinfolds (triceps, subscapular, biceps, iliac crest, supraspinale, abdominal, front thigh and medial calf) were measured to the nearest 0.2 cm using a Harpenden skinfold caliper (British Indicators Ltd, St Albans, UK). Bone breadths and segmental girths were measured by a small bone sliding caliper (Rosscraft Innovations Inc, Vancouver, Canada) and a retractable measuring tape (Cooper Industries, Sparks, US), respectively.

Treadmill Incremental test.

All race walkers completed an incremental test on a treadmill (3p pulsar, H/P/cosmos, Germany) set at a 1% gradient (Jones & Doust, 1996). The treadmill was calibrated using a measuring wheel (ERGelek, Vitoria-Gasteiz, Spain) with a measurement error <0.5 m per 100 m interval. The test started at 10 km·h^{-1} without previous warm up and the speed was increased by 1 km·h^{-1} every 3 min until volitional exhaustion, with 30 s of recovery between stages (Bär, 1990). The analysed speeds were selected based on intensities corresponding to typical warm-up pace (10 km ·h^{-1}), long-walk training pace (12 km·h^{-1}) and Tempo training pace (14 km·h^{-1}).

During the test, heart rate was recorded every 5 seconds continuously by a heart rate monitor (Polar RS800, Kempele, Finland) and respiratory variables were continuously measured using a gas analyser system (Ergostik, Geratherm, Germany) calibrated before each session. Volume calibration was performed at different flow rates with a 3 L calibration syringe (Ergostik, Geratherm, Germany) allowing an error ≤ 2%, and gas calibration was performed automatically by the system using both ambient and reference gases (CO_2 4.10%; O_2 15.92%) (Linde Gas, Germany).

In consideration of the slow component in oxygen uptake ($\dot{V}O_2$), a slow increase in $\dot{V}O_2$ during a constant-work-rate exercise performed above the lactate threshold (Jones et al., 2011), $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$) values collected during the last 30 s of three different speeds under the lactate threshold for all race walkers were averaged and designated as steady-state race walking economy ($ml \cdot kg^{-1} \cdot km^{-1}$). This was performed to ensure steady-state $\dot{V}O_2$ values and to avoid possible biomechanical differences as a consequence of differing race walking speeds.

Immediately, after each exercise stage, capillary blood samples from the earlobe were obtained and analysed with a portable lactate analyser (Lactate Pro2, Arkray, KDK Corporation, Kyoto, Japan) to determinate the lactate concentrations ($[La^-]$). The lactate threshold of each participant was determined using a third order polynomial regression equation calculated with the plasma $[La^-]$ versus speed (Santos-Concejero et al., 2014). The point on the polynomial regression curve that yielded the maximal distance to the straight line formed by the two end data points was identified as the lactate threshold (Cheng et al., 1992).

Biomechanics.

The spatiotemporal assessment was conducted during the treadmill test using an optical measurement system (Optojump-next, Microgate, Bolzano, Italy). The values of the 2nd and 3rd min of the race walking stages corresponding to 10, 12 and 14 $km \cdot h^{-1}$ were averaged and used for data analysis.

Optojump-next system consists of two bars (size 100 × 3 × 4 cm), one containing the reception and control unit, the other embedding the transmission electronics. Each of these contains 32 light emitting diodes (LEDs), positioned 0.3 cm from ground level at 3.125 cm intervals. The LEDs on the transmitting bar communicate continuously (1 kHz) with those on the receiving bar and has been shown to accurately determine gait spatiotemporal variables (Alvarez, Sebastian, Pellitero, & Ferrer-Roca, 2017). Gait cycle characteristics determined were ground contact time, swing time, step length, cadence and the percentage of the stance phase at which the different sub-phases occurs (initial contact, midstance and propulsion) (Padulo, Chamari, & Ardigò, 2014). During stance, the subphases were defined as: the initial contact sub-phase corresponds to the time from *initial ground contact* to *foot flat*; the midstance sub-phase from *foot flat* to *initial take off* and the propulsive sub-phase from *initial take off* to *toe off*.

Statistical analysis

All values are expressed as mean ± standard deviation (SD) and statistical analyses of data were performed using IBM SPSS 21 (IBM Corporation, Armok, USA). Data were screened for normality of distribution and homogeneity of variances using a Shapiro-Wilk normality test and a Levene's test respectively. The magnitude of differences or effect sizes (ES) were calculated according to Cohen's d and interpreted as small (>0.2 and <0.6), moderate (≥0.6 and <1.2) and large (≥1.2 and <2) according to the scale proposed by (Hopkins et al., 2009). Pearson's product-moment correlations were used to assess the relationships between spatiotemporal variables of the gait cycle and race walking economy and interpreted as small (>0.1 and <0.3), moderate (≥0.3 and <0.5), large (≥0.5 and <0.7) and very large (≥0.7 and <0.9). A linear regression was performed to analyse the relationships between race walking economy and performance and 95% confidence intervals were calculated. Linear regression assumptions were checked using residual versus fitted, normal QQ, and Cook's distance plots. Significance for all analyses was set at $p<0.05$.

5.3.3 Results

Descriptive characteristics

The physiological variables and descriptive characteristics of the race walkers participating in this study are listed in Table 4. All athletes possessed a personal best time faster than the entry standard needed to participate in the Olympic Games of Rio de Janeiro 2016 (1:24:00 for men), confirming that all participants were world-class elite race walkers. The homogeneity of the group was confirmed by a coefficient of variation < 10% for all anthropometrical (except the ∑ 8 skinfold), physiological and performance related variables, including their personal best 20-km race walking times.

Table 4. Physical and physiological characteristics of elite race walkers (n = 21).

	Mean ± SD	CV (%)
Age (years)	26.6 ± 5.5	20.8
VO_2 at 14 km·h^{-1} (mL·kg^{-1}·min^{-1})	56.3 ± 3.5	6.2
20-km PB (min)	80.4 ± 2.1	2.7
LT (km·h^{-1})	14.6 ± 0.5	3.4
Race walking economy (mL·kg^{-1}·km^{-1})	241.3 ± 14.9	6.2
Height (cm)	177.1 ± 7.1	4
Mass (kg)	66.4 ± 5.8	8.7
∑ 8 skinfold (mm)	49.3 ± 6.8	13.7

n, number of participants; CV, coefficient of variation; VO2 at 14 km·h−1, oxygen uptake at 14 km·h−1; PB, personal best; LT, lactate threshold; ∑ 8 skinfolds: biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh, and medial calf. Values are means ± SD.

Figure 3 illustrates the relationship between race walking performance according to their best 20-km race time and race walking economy. Race walking economy at 14 km·h^{-1} was positively correlated with performance (R=0.760, p<0.001; very large effect).

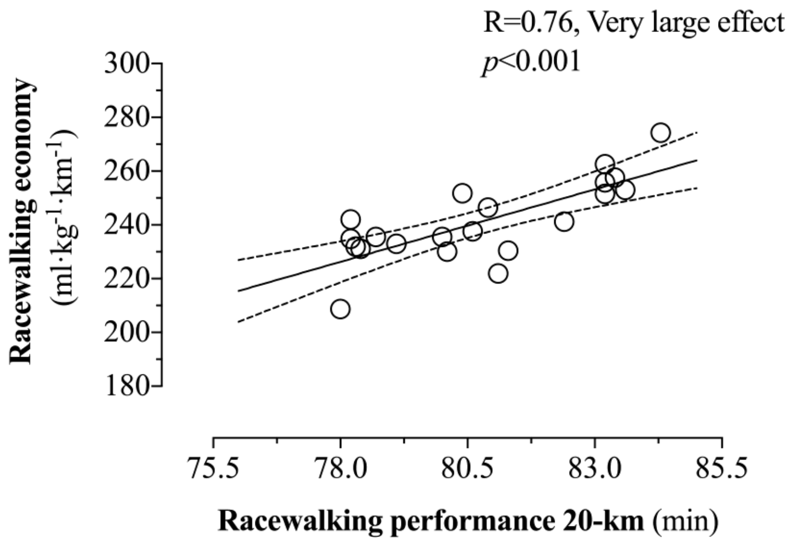

Figure 3. Relationship between race walking economy and participants' personal best performance in 20 km (n=21). 95% confidence intervals are shown.

Figure 4 and 5 depict changes in spatiotemporal parameters of the gait cycle as walking speeds increase. At increasing race walking speeds, step length and walking cadence increased by 24.8% and 12.2%, respectively. Ground contact time decreased from 0.34 ± 0.01 s at 10 km·h^{-1} to 0.28 ± 0.01 s at 14 km·h^{-1}, whereas the flight time increased from a double support to a flight time of 0.026 ± 0.007 s at 14 km·h^{-1}. Similarly, increasing race walking speeds were accompanied by a reduction of the initial contact sub-phase and propulsive sub-phase times in 19.1% and 29.7%, respectively. On the other hand, midstance sub-phase time increased in 101.1%.

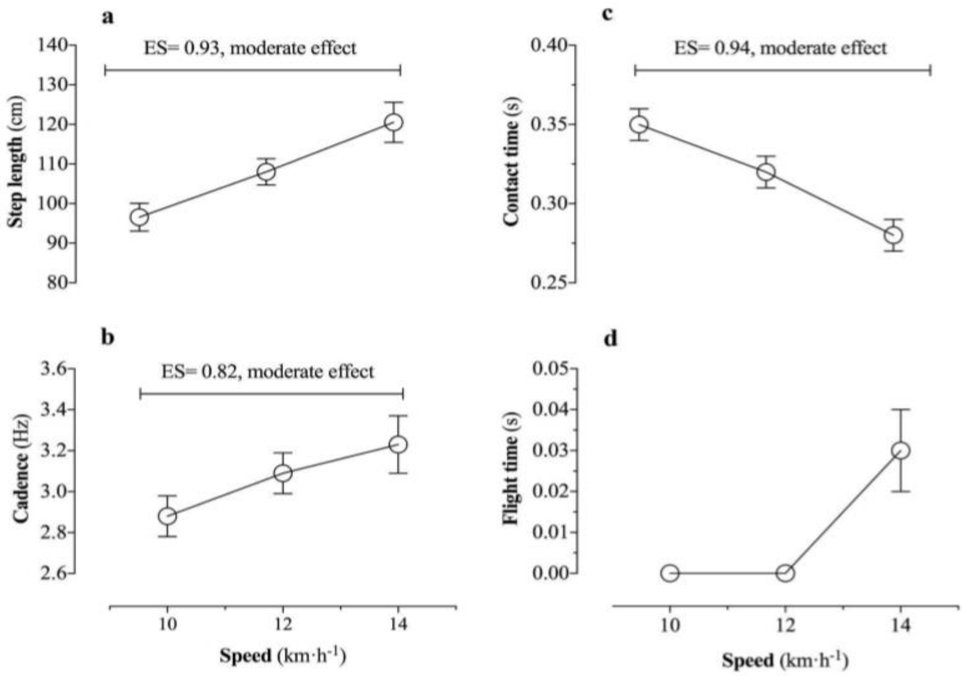

Figure 4. Step length (A), Step frequency (B), contact time (C) and flight time (D) at different speeds (n=21).

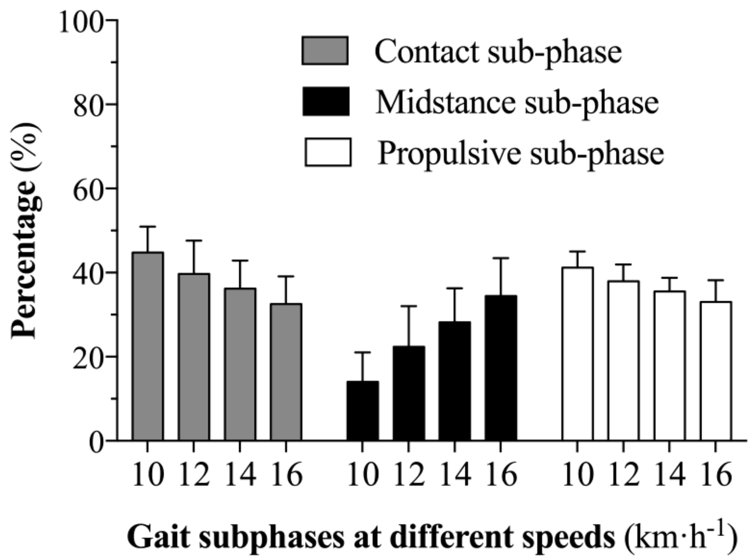

Figure 5. Percentage of time spent in each sub-phase of the stance phase (initial contact, midstance and propulsive) at different speeds (n=21).

Correlations between spatiotemporal gait variables and race walking economy at different speeds are depicted in Table 5. Significant correlations between flight time (s) at 12 km·h^{-1} (moderate effect) and 14 km·h^{-1} (moderate effect) were observed. Similarly, the percentage of the gait cycle spent in the swing phase correlated positively with race walking economy at 12 km·h^{-1} (large effect) and at 14 km·h^{-1} (large effect), whereas ground contact time (s) at 12 km·h^{-1} and 14 km·h^{-1} was negatively associated with race walking economy (large effect and moderate effect). The percentage of the gait cycle spent in the stance phase also correlated significantly with race walking economy at both 12 and 14 km·h^{-1} (large effect). Lastly, the midstance sub-phase showed a significant correlation with race walking economy at 12 km·h^{-1} (moderate effect) and at 14 km·h^{-1} (moderate effect), whereas the propulsive sub-phase correlated only at 12 km·h^{-1} (moderate effect).

Table 5. Interrelationships between biomechanical variables and race walking economy at different speeds (n = 21).

Race walking economy	10 km·h^{-1}		12 km·h^{-1}		14 km·h^{-1}	
	r	***p***	***r***	***p***	***r***	***p***
Step length (cm)	-0.327	NS	-0.398	NS	-0.116	NS
Ratio height:step length	-0.082	NS	-0.193	NS	0.051	NS
Cadence (step/s)	0.333	NS	0.397	NS	0.123	NS
Contact time (s)	-0.253	NS	**-0.524**	**0.015**	**-0.448**	**0.042**
Flight time (s)		NS	**0.477**	**0.029**	**0.487**	**0.025**
Stance phase (%)		NS	**-0.543**	**0.011**	**-0.607**	**0.004**
Swing phase (%)		NS	**0.543**	**0.011**	**0.607**	**0.004**
Initial contact sub-phase (%)	0.358	NS	0.318	NS	0.371	NS
Midstance sub-phase (%)	-0.386	NS	**-0.454**	**0.039**	**-0.460**	**0.036**
Propulsive sub-phase (%)	0.129	NS	**0.470**	**0.032**	0.382	NS

r, Pearson correlation coefficient; *p*, significance; NS, no significant differences.

5.4 Study 4: Biomechanical analysis of gait waveform data in elite race walkers and runners.

5.4.1 The aim of the study

Either running and race walking have been studied independently. As most studies have rather observed gait differences between training populations (recreational, national, elite) in race walkers or runners but not between disciplines (Cronin, Hanley, & Bissas, 2016; Rogers, Whatman, Pearson, & Kilding, 2017). A comprehensive understanding of gait waveforms, whether kinetic or kinematic, during running and race walking in elite athletes provide insight into the specific and well-defined demands of these different gait disciplines. The use of one-dimensional statistical parametric mapping (1DSPM) provides the temporal assessment of gait data, that allows a broader understanding of the modifications required throughout the gait cycle that enable race walkers to maintain velocities similar to those of runners, (Vanrenterghem, Venables, Pataky, & Robinson, 2012). Thus, the aim of this study was to analyse and compare the kinematics and kinetics of the gait cycle in world-class runners and race walkers using three-dimensional motion capture and force platform data. Additionally, these types of data analysis techniques can contribute to our better understanding of the gait sub phases.

5.4.2 Methods

Participants

Twenty-one elite male race walkers (20 km: 80.8 ± 2.1 min) and 15 elite male endurance runners (21.1 km: 62.2 ± 1.0 min) agreed to participate in this study. All participants were informed about all tests and possible risks involved and provided written informed consent before testing. The Ethics Committee for Research on Human subjects of the University of the Basque Country (CEISH 66/2015) and the Research Ethics Committee of the University of Cape Town (HREC ref 151/2013) approved this study.

Design and protocol

Anthropometric characteristics of the participants, comprising height, mass and the sum of eight skinfolds (∑ 8 skinfolds: biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh and medial calf) were measured. The measurement of running and race walking economy was achieved by a constant running/race walking test (12 $km \cdot h^{-1}$) completed on a treadmill (3p pulsar, h/p/cosmos, Germany) (Gomez-Ezeiza et al., 2018). The speed of 12 $km \cdot h^{-1}$ was chosen to allow the comparison between both running and race walking at a constant submaximal speed, avoiding any fatigue interference in the participants' gait patterns.

Participants completed race walking trials on a 30-m track in an indoor laboratory and were not provided with any technical instruction. During this time, three-dimensional marker trajectories were captured at 250 Hz, using a 10-camera Vicon Bonita motion capture system (Vicon, Oxford, UK). Synchronised collection of ground reaction force (GRF) data was sampled at 2000 Hz using a 900 × 600 mm force platform (AMTI, Watertown, MA, USA). Prior to testing, reflective markers were attached according to a modified Helen-Hayes Marker set (Tam, Tucker, Santos-Concejero, Prins, & Lamberts, 2018). The speed of the trials was set at 12 $km \cdot h^{-1}$ and accepted if the speed was within ± 4% of the target speed, when all markers were in view of the cameras and there was no visual evidence of athletes targeting the force platform.

Data analysis

For each trial, a complete gait of the participant`s right limb was analysed (ground contact-ground contact). Marker trajectory and force platform data were filtered using a low-pass fourth-order Butterworth filter with cut-off frequencies of 20 and 100 Hz respectively. Three-dimensional joint angles (ankle, knee and hip) were determined using the *PlugInGait* model and net resultant joint's sagittal moments using a Newton-Euler inverse dynamics approach (Winter, 1980). Joint moments were expressed as external moments normalised to body mass ($Nm \cdot kg^{-1}$). Additionally, GRF data were normalised to bodyweight (BW) and the initial rate of loading was calculated (Williams, Snow, & Agruss, 1991). Subsequently, joint kinematic and kinetic data are presented as waveforms that changed continuously throughout the entire gait cycle (101 data points), except for the vertical GRF waveform that is normalised to percentage of stance (101 data points).

Statistical analysis

Data were screened for normality of distribution using a Shapiro-Wilk's Normality test. Differences in descriptive characteristics, initial loading rate and ground contact time were assessed using independent *t*-tests or non-parametric Wilcoxon sign rank test, where appropriate. To detect differences between the kinematic and kinetic waveforms, 1DSPM was employed (Vanrenterghem, Venables, Pataky, & Robinson, 2012). The running and race walking gait waveforms were compared using a one-way analysis of variance (SPM{f}). All 1DSPM analyses were implemented using the open-source 1DSPM code (v.M0.1, www.spm1d.org) in MATLAB (R2014a, 8.3.0.532, MathWorks Inc., Natick, MA, USA).

5.4.3 Results

The athletic discipline specificity between groups resulted in large differences, as the race walkers were taller (P=0.009), heavier (P=0.004), greater ∑ 8 skinfolds (P=0.006) and higher oxygen cost of transport at 12 km·h^{-1} (P=0.001) (Table 6). Race walking and running speeds were similar between groups, however, differences in discrete kinetic and spatiotemporal variables were found (Table 6). To maintain a similar speed, race walkers exhibited longer ground contact times (P=0.001) and shorter swing times (P=0.001) than the runners. Additionally, race walkers also presented shorter strides (P=0.001) and higher cadences (P=0.001).

Table 6. Comparison of physical, physiological and gait characteristics (at 12 km· h−1) of elite long-distance runners and race walkers.

	Race walkers (*n*=21)	**Runners** (*n*=15)
IAAF performance (u)	1184 ± 44 (20 km RW)	1100 ± 37 (21.097 km)
Age (years)	26.6 ± 5.5	23.7 ± 4.1
Height (m)	1.77 ± 0.07	1.71 ± 0.06**
Mass (kg)	66.4 ± 5.8	54.8 ± 6.0**
∑ 8 skinfold (mm)	49.3 ± 6.8	35.7 ± 8.6**
Economy at 12 km·h^{-1} (mL·kg^{-1}·km^{-1})	236.8 ± 16.2	192.6 ± 11.1**
Initial loading rate (BW·s^{-1})	27.67 ± 5.90	84.63 ± 36.92**
Ground contact time (s)	0.322 ± 0.011	0.237 ± 0.016**
Swing time (s)	0.304 ± 0.010	0.498 ± 0.044**
Step length (m)	1.08 ± 0.06	1.35 ± 0.10**
Cadence (step·s^{-1})	3.09 ± 0.10	2.47 ± 0.18**
Early stance (%)	0-16	0-13

Late stance (%)	17-46	14-36
Swing phase (%)	47-100	37-100

n: number of participants; ∑ 8 skinfolds: biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh and medial calf. Values are mean ± SD. Statistically significant difference $*p < 0.05$, $** p < 0.01$.

Large kinematic waveform differences were found between running and race walking at the same speed (Table 7 and Figure 6). Especially, in the sagittal plane, hip flexion-extension range of motion was more restricted in the race walkers than the runners between 0-81% of the gait cycle (F=7.935; P=0.011). In addition, greater knee extension was observed in the race walkers when compared with the runners throughout the gait cycle and an absent knee flexion peak during stance phase (F=8.142; P=0.001). Ankle dorsiflexion range of motion in the race walkers compared with runners was decreased with a later and smaller peak dorsi- and plantarflexion during stance at 0-47% of the gait cycle (F=8.271; P=0.001). In the frontal plane, decreased range of motion was found during stance in the race walkers in both the knee and ankle when compared with the runners at 20-48% and 0-46% of the gait cycle, respectively (F=8.142; P=0.008 and P=0.001, respectively). Greater ranges of motion in hip adduction-abduction were found in the race walkers than runners between 0-16% and 36-100% of the gait cycle (F=7.935; P=0.018 and P=0.004). Moreover, only the ankle exhibited differences in the transverse plane, where race walkers remained in greater ankle external rotation during stance (0-40%), early mid-swing (48-80%) and terminal swing (96-100% of the gait cycle) when compared with the runners (F=8.271; P=0.001, P=0.002 and P=0.001, respectively).

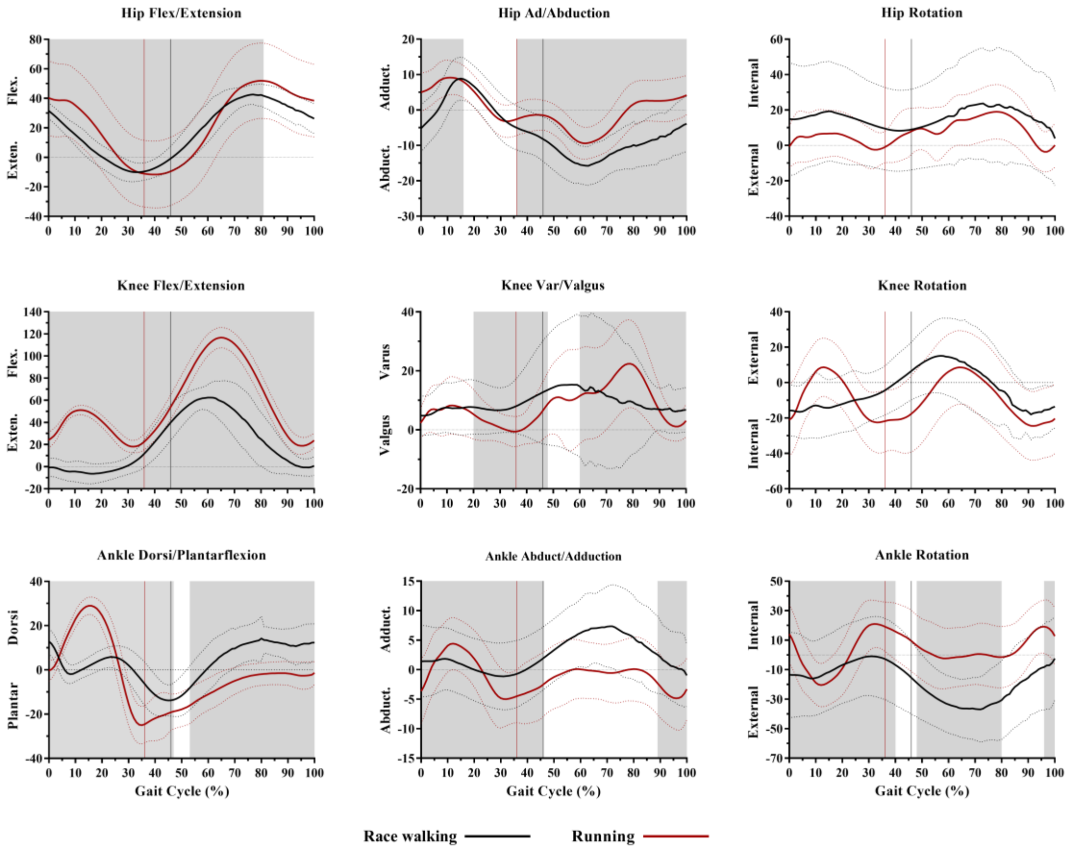

Figure 6. Kinematic data over an entire gait cycle. Mean ± SD for race walkers (constant line) and runners (dashed line). GREY bars denote periods where there were differences between-group.

With regard to joint kinetic waveforms, runners exhibited greater hip flexion moments between 0-14% and 20-42% of the gait cycle when compared with the runners (Table 7). Runners presented with greater knee flexion moments at 1-5% and 7-38% of the gait cycle than the race walkers. Thereafter, knee flexion moments were greater in the race walkers over 28-38% of the gait cycle when compared with the runners. The ankle flexion moment was lower in the race walkers from 2-23%, and thereafter greater during 24-40% of the gait cycle when compared with the runners. Lastly, there was greater vertical GRF in the runners than the race walkers between 19-77% of the stance phase (Figure 7). Race walkers and runners showed similar GRF patterns during initial contact. However, the initial loading rate was higher in the runners (P=0.011) (Table 7).

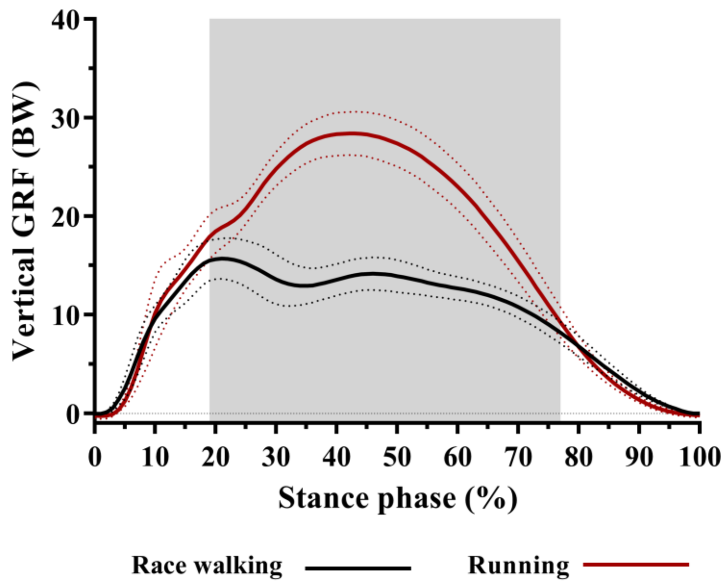

Figure 7. Ground reaction forces data over the stance phase. Mean ± SD for race walkers (constant line) and runners (dashed line). GREY bars denote periods where there were differences between-group.

Table 7. Summary table with respect to SPM analyses.

Variables	Critical threshold exceeded (% of gait cycle)	Supra-threshold p-values	Critical threshold (*f)
Kinematics			
Hip			
Sagittal plane	Stance and swing (0-81%)	p = 0.011	F = 7.935
Frontal plane	Early stance (0-16%)	p = 0.018	
	End stance and swing (36-100%)	p = 0.004	
Knee			
Sagittal plane	Entire cycle (0-100%)	P = 0.001	F = 8.142
Frontal plane	Mid stance and early swing (20-48%)	P = 0.008	
	Swing (60-100%)	P = 0.006	
Ankle			
Sagittal plane	Stance and early swing (0-47%)	P = 0.001	F = 8.271
	Swing (53-100%)	P = 0.013	
Frontal plane	Stance (0-46%)	P = 0.001	
	Late swing (89-100%)	P = 0.014	
Transverse plane	Stance (0-40%)	P = 0.001	
	Swing (48-80%)	P = 0.002	
	Late swing (96-100%)	P = 0.001	
Moments			
Hip			
Sagittal plane	Early stance (0-14%)	P = 0.001	F = 11.943
	Late stance (20-42%)	P = 0.002	

Knee			
Sagittal plane	Early stance (1-5%)	P = 0.001	F = 12.223
	Early and Midstance (7-38%)	P = 0.001	
Ankle			
Sagittal plane	Early stance and early swing (2-40%)	P = 0.038	F = 12.182
Ground Reaction Force			
Vertical	Mid stance (19-77%)	P = 0.001	F = 8.998

5.5 Study 5: “Muscle activation patterns correlate with race walking economy in elite race walkers: a waveform analysis”

5.5.1 The aim of the study

Understanding the influence of muscle activation on oxygen cost of transport in race walkers is of interest as it provides insight into regulation of race walking kinematics that are associated with metabolic efficiency a marker of performance. Additionally, this analysis may give new insights in coaching race walkers, with regard to the development of specific training strategies that consider the specific biomechanical and physiological demands of race walking. Thus, the aim of this study was to analyse the influence of muscle activation patterns on oxygen cost of transport in elite race walkers over the entire gait waveform.

5.5.2 Methods

Participants

Twenty-one male Olympic race walkers agreed to participate in this study. All athletes possessed the 2016 Olympic Entry Standard for Rio de Janeiro (84 minutes for 20-km). All participants were informed about all tests and possible risks involved and provided written informed consent before testing. The Ethics Committee for Research on Human subjects of the University of the Basque Country (CEISH 66/2015) approved this study.

Design and protocol

Twenty-four hours before testing, the participants were required to abstain from a hard training session or competition to be well rested. They were also requested to maintain their pre-competition diets throughout the test procedures and to abstain from caffeine and alcohol intake the day before testing. All testing sessions were performed under similar environmental conditions (20 – 23ºC and between 09:00 – 13:00). Anthropometric characteristics of the participants, comprising height, mass and the sum of eight skinfolds (biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh and medial calf) were measured.

Participants completed race walking trials on a 30-m track in an indoor laboratory and were not provided with any technical instruction. During this time, synchronized collection of three-dimensional markers trajectories using a 10-camera Vicon Bonita 10 motion capture system (Vicon, Oxford, UK), ground reaction force data (AMTI, Watertown, MA, USA) and wireless surface electromyography (myON 320, Schwarzenberg, Switzerland) were recorded. The six muscles of interest for electromyography were gluteus maximus, adductor magnus, rectus femoris, biceps femoris, medial gastrocnemius and tibialis anterior. Before assessment, skin areas were prepared, and two surface electrodes placed according to established guidelines (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Leads and pre-amplifiers connected to the electrodes were secured with medical grade tape to avoid artefacts from lower limb movement during gait. The speed of the trials was set at 14 $km \cdot h^{-1}$ and trials were accepted if the speed was within ± 4% of the target speed, the entire right-foot made contact with a force platform and an entire gait cycle was visible from there on (ground contact-ground contact of the right foot). Motion capture and ground reaction force data were used only for gait event detection in this study.

Subsequently, race walking economy was determined by performing an incremental treadmill test (3p pulsar, h/p/cosmos, Germany). The slope was set at a 1% gradient (Jones & Doust, 1996) and the test started at 10 $km \cdot h^{-1}$; after 3 min, the speed was increased by 1 $km \cdot h^{-1}$ every 3 min until 14 $km \cdot h^{-1}$ was completed, the velocity used for analysis. A 30 s recovery was taken between stages. During the test, oxygen uptake (VO_2) was continuously measured using a gas analyser system (Ergostik, Geratherm, Germany). To ensure VO_2 steady-state measurements, the speed selected (14 $km \cdot h^{-1}$) was slower than the individual lactate threshold of each athlete (further confirmed during the test by respiratory exchange ratios below 1.0 during the whole running bout for all athletes at each speed). VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$) values collected during the last 30 s of each stage were averaged and designated as steady-state race walking economy ($mL \cdot kg^{-1} \cdot km^{-1}$) to avoid the slow component in VO_2 (Santos-Concejero et al., 2014).

Data analysis

The raw digital electromyography signal of sub-maximal trials were bandpass filtered between 30-450 Hz, then rectified and smoothed using root mean square (RMS) analysis at a 50 ms moving window (Albertus-Kajee, Tucker, Derman, Lamberts, & Lambert, 2011). Additionally, the EMG signals were normalised to each muscle activation peak. Subsequently, electromyography data were reduced to 101 points and presented as waveforms that changed continuously throughout the race walking gait cycle (a point per percentage of the gait cycle).

Statistical analysis

Data were screened for normality of distribution using a Shapiro-Wilk's Normality test. To detect relationships between muscle activity waveforms with race walking economy (at 14 km·h^{-1}), one-dimensional statistical parametric mapping (1DSPM) regression was employed (Pataky, Vanrenterghem, & Robinson, 2015). The 1DSPM analyses were implemented using the open-source 1DSPM code (v.M0.4, www.spm1d.org) in Python (2.7, Python Foundation, USA). Significance for regressions were accepted at $p<0.05$.

5.5.3 Results

The descriptive characteristics and physiological variables of the race walkers participating in the study are presented in Table 8. Specifically, this cohort presented a mean 20-km race performance of 80.49 ± 2.12 min and a race walking economy of 241.32 ± 14.91 mL·kg^{-1}·km^{-1}.

Table 8. Physical and physiological characteristics of the race walkers (n=21).

	Mean ± SD
Age (years)	26.62 ± 5.53
Height (cm)	177.11 ± 7.13
Mass (kg)	66.41 ± 5.77
∑ 8 skinfold (mm)	49.33 ± 6.78
20-km race time (min)	80.49 ± 2.12
Race walking economy (mL·kg^{-1}·km^{-1})*	241.32 ± 14.91

*: at 14 km·h^{-1}

Posterior muscle activity and race walking economy

Relationships between posterior muscle activation and race walking economy were found in elite race walkers are listed in Table 9. During terminal swing (biceps femoris: 96-100% of the gait cycle, p=0.010, r=-0.801; gluteus maximus: 98-100%, p=0.022, r=-0.716) and initial weight acceptance (biceps femoris: 0-4%, p=0.011, r=-0.809; gluteus maximus: 0-6%, p=0.011, r=-0.723), higher activation of biceps femoris and gluteus maximus were associated with better race walking economy (Figure 8). Additionally, a higher activation of the medial gastrocnemius during weight acceptance (5-8% of the gait cycle, p=0.041, r=-0.662) was found in more economical race walkers. During the propulsion phase a greater medial gastrocnemius activation was also associated with a lower oxygen cost of transport (20-27% of the gait cycle, p=0.039, r=-0.668). Lastly, a lower activation of the biceps femoris was associated with more economical race walkers at 36-43% of the gait cycle (late propulsive phase to toe-off, p=0.012, r=0.697).

Table 9. Summary table with respect to SPM analyses. Presented outcomes for regression of race walking race walking economy and muscle activity.

Muscles	**Critical threshold exceeded (% of gait cycle)***	**Supra-threshold p-values**	**r-values**
Gluteus Maximus	Weight acceptance (0-4%)	0.011	-0.723
	Swing (98-100%)	0.022	-0.716
Adductor Magnus	Swing phase (43-50%)	0.041	0.690
Biceps Femoris	Weight acceptance (0-6%)	0.011	-0.809
	Propulsive phase (38-43%)	0.012	0.697
	Swing (96-100%)	0.010	-0.801
Rectus Femoris	Weight acceptance (8-11%)	0.016	-0.678
	Weight acceptance (18-23%)	0.034	0.637
	Propulsive phase (35-41%)	0.018	-0.798
	Swing phase (42-53%)	0.018	-0.798
	Swing phase (63-68%)	0.021	-0.813
Gastrocnemius	Weight acceptance (5-8%)	0.041	-0.662
	Propulsive phase (20-27%)	0.039	-0.668
Tibialis Anterior	Weight acceptance (6-12%)	0.033	0.671

SPM, Statistical parametric mapping; *Critical threshold (*f) was calculated at F=3.96.

Anterior activity and race walking economy

During weight acceptance of ground contact, greater rectus femoris activation was associated with the most economical race walkers (8-11% of the gait cycle, p=0.016, r=-0.678). This coincided with a lower tibialis anterior activation at 6-12% of the gait cycle was associated with efficient race walking economy (p=0.033, r=0.671) (Figure 8), whereas, during the propulsive phase (18-23% of the gait cycle) lower rectus femoris activation was associated better race walking economy (p=0.034, r=0.637). Subsequently, at the end of the propulsive phase (35-41% of the gait cycle), early- and mid-swing (42-53% and 63-68% of the gait cycle) greater rectus femoris activation was associated with lower oxygen cost of transport (p=0.018, r=-0.798; p=0.018, r=-0.798 and p=0.021, r=-0.813). Lastly, lower adductor magnus activation during early swing (43-50% of the gait cycle) was associated with better race walking economy (p=0.041, r=0.690).

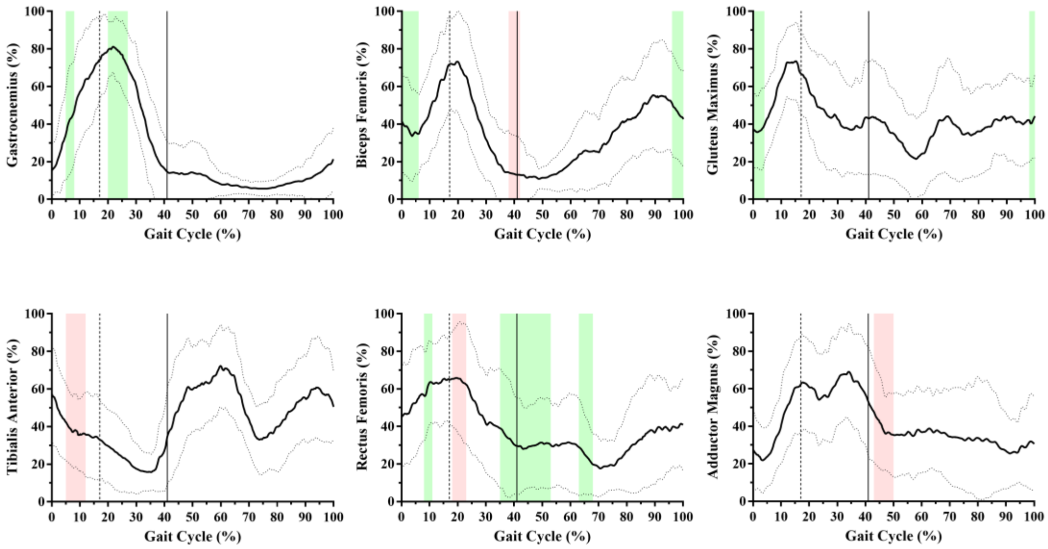

Figure 8. Muscle activation data over an entire gait cycle. Mean ± SD for each muscle. GREEN bands, negative correlation between muscle activation and oxygen uptake; RED bands, positive correlation between muscle activation and oxygen uptake.

6

DISCUSSION

“The most exciting phrase to hear in science, the one that heralds the most discoveries, is not "Eureka!" but "that's funny...”

Isaac Asimov

6. Discussion

6.1 Anthropometric characteristics of top-class Olympic racewalkers

The main finding of this study was that sex differences were found for all key anthropometrical characteristics required to excel in endurance events. In addition, males competing in the 50- and 20-km race walking events also presented differences in certain variables. These results suggest that unique anthropometric profiles are suited to each event. Previous research has shown the positive influence of certain anthropometrical characteristics on endurance performance (Basset et al., 2014; Carlsson et al., 2014; Knechtle, 2014; Stellingwerff, 2018). Of these, the most used anthropometrical parameter in endurance athletes is the sum of skinfolds, often reported as an important predictor of endurance performance (Legaz-Arrese, Kinfu, Munguía-Izquierdo, Carranza-Garcia, & Calderón, 2009). Previous studies analysing elite endurance athletes have reported low skinfold thickness and body fat content, which is in agreement with the results of this study (Basset et al., 2014; Carlsson et al., 2014; Knechtle, 2014; Stellingwerff, 2018). For instance, a lower sum of skinfolds was found in the 50-km male racewalkers when compared to their 20-km male counterparts. Similarly, Legaz-Arrese, Badillo & Ostariz (2005) found lower skinfold thickness in marathon runners than athletes competing over shorter distances. This lower sum of skinfold is representative of a reduced subcutaneous fat and gross mass, which may consequently reduce the muscular effort required to maintain the same walking intensity (Teunissen, Grabowski, & Kram, 2007). Interestingly, a lower sum of skinfolds and body fat content was found in male race walkers when compared to female walkers. This is in agreement with other studies describing sex differences in multiple athletic disciplines (Knechtle, Knechtle, Barandun, Rosemann, & Lepers, 2011).

It is known that endurance training regimes result in specific anthropometric adaptations (Knechtle, Knechtle, & Rosemann, 2010). To our best knowledge, there is a lack of longitudinal data describing anthropometrical changes associated with training regimes of elite race walkers. However, this can be inferred taking into account the seasonal training load of elite race walkers (Gomez-Ezeiza et al., 2016). It has been reported that the training regime of an elite race walker consists of very high training volumes at low intensities, divided into phases where training load is variable (volume/intensity). Specifically, Knechtle et al. showed that weekly training volumes are associated to lower sum of skinfolds and body fat percentages (Knechtle et al., 2010). These changes, and other factors like injuries, illnesses, recovery phases, altitude training camps etc. may also contribute to changes in body composition during the season (Heydenreich et al., 2017). Considering the years of continuous training spent by athletes in a high-performance environment, certain anthropometric adaptations during the whole period are expected.

With the aim of reducing body fat mass, some endurance athletes use nutritional interventions (Martinsen et al., 2010). However, a reduction of energy availability may concomitantly be associated with a loss of muscle mass (Heydenreich et al., 2017), which may result in a reduced capacity to produce optimal muscle-power (Stellingwerff, 2018). In this study, a greater muscle mass was found in both 20- and 50-km elite race walkers (38.0 ± 2.9 and 36.5 ± 3.3 kg) when compared to elite endurance athletes from other studies such as Kenyan runners (33.2 kg, ES=0.76, moderate effect) (Vernillo et al., 2013) or European runners (Santos-Concejero et al., 2013). Higher muscle mass in the race walkers may be explained by the greater muscle demand and effort needed to maintain the race walking gait patterns (Cronin et al., 2016). Unlike running, the rules that govern race walking force the race walker to limit the gait to a less efficient pattern. Specially, the lack of knee flexion that does occur during stance phase has been shown to result in a reduced energy-saving role of the Achilles tendon, in addition to higher muscle effort done by the use of a) longer propulsive phases, b) higher stride frequencies, c) greater action of the upper-body; making race walking mechanically more costly than running at the same speed (Hoga et al., 2015; Gomez-Ezeiza, 2018).

In this study, the somatotype categorisation in male and female race walkers was compared to assess morphology according to the relative contribution of three fundamental elements: mesomorphy, ectomorphy and endomorphy. A study conducted by Vernillo (2013) reported the ectomorphic character that showed elite Kenyan marathon runners, related to a relative linearity and long-line body types. However, the results of this study show that elite race walkers exhibited a balanced mesomorph-ectomorph somatotype dimension. This morphological body-type is characterised by an athletically balanced element of a longilinear athlete with well-developed muscles. Although all groups in this study presented a balanced mesomorph-ectomorph somatotype, distance specialised group (20-km vs. 50-km) exhibited a specific somatotype-rating trend related to the values of each somatotype category. These anthropometrical and morphological differences may be a result of the different training approaches from the different competitive distances. The higher training volumes at low intensities employed by the 50-km race walkers may rely on the use of fat metabolism and imply a reduced energy availability (Tam et al., 2017). This may induce adaptations in lower sum of skinfolds, favouring a more ectomorphic somatotype profile. In contrast, race walkers competing over 20-km train at a higher intensity and speed (Drake, 2005), resulting in slightly greater muscle mass values and more mesomorphic profiles.

This study faced several limitations. The first limitation of this study is the error in anthropometric manual measurement, the technique used, the equipment, the formula used, and the site location, as all these factors can affect the results. However, since the anthropometrical measurements were performed by an accredited anthropometrist following standardised techniques, we believe that the measurement error was negligible. In the future, the use of dual energy X-ray absorptiometry (DXA) could most appropriately assess the anthropometrical characteristics of elite race walkers (Ball, Altena, & Swan, 2004).

6.2 The influence of race walking on the calcaneal bone density in world-class male and female race walkers

The main goal of this study was to analyse and compare calcaneal stiffness, a marker of bone mineral density (BMD), in elite 20-km and 50-km male and 20-km female race walkers. It was hypothesized that, due to the specific gait pattern employed by race walkers and distance specific training, calcaneal stiffness may differ between these groups. Indeed, within the race walking group differences were found in various bone ultrasonographic parameters between sex and competitive distances, however, no differences were found between the race walkers and control group.

The first notable finding was that the 50-km male race walkers presented lower SOS, SI, T- and Z-score values but not BUA values when compared to the 20-km male race walkers. The lower SOS values suggest the 50-km male race walkers possess lower soft tissue and differing micro-architecture of cortical thickness/elasticity that comprises of the bone (Lara et al., 2016). This subsequently results in a lower SI, T- and Z-scores and these discrepancies maybe a related to differences found in training volume and intensity between these athletes of different distance specialization. Interestingly, a correlation between weekly training load and BUA values of the entire race walking group was found, where a greater training load was associated with a lower BUA, a marker of BMD (Cepollaro et al., 1995). Previous studies have found that recreational marathon runners possess greater calcaneal stiffness than half-marathon and 10-km runners (Lara et al., 2016). However, our current findings in race walker suggest that too high training volumes may expose one to lower bone quality, especially when comparing elite to recreational athletes. This and a previous study have described that elite race walkers' training regimes consist of very high training volumes at low and moderate intensities (Gomez-Ezeiza et al., 2015). These demanding training regimes increase the risk of low energy availability (Mountjoy et al., 2018), usually associated with endurance athletes (Smathers, Been, & Been, 2009). Low energy availability alters the endocrine system (Lombardi, Sanchis-Gomar, Perego, Sansoni, & Banfi, 2015), with negative consequences on BMD (Papageorgiou et al., 2017). Thus, the observed lower SOS, SI, T- and Z-score values found in the 50-km race walkers, suggest lower bone quality that appears to be related to possible energy availability from high training volumes and subsequent disruption in bone turnover and consolidation which may increase injury risk.

Moreover, the 50-km race walkers exhibited below normal T- and Z-score values (-0.8 ± 1.3 & -0.8 ± 1.2, respectively). Indeed, five of the eight (62.5%) 50-km race walkers in this study presented values of T- and Z-scores below -1.0, classifying them as osteopenic according to the World Health Organization classification system (Pollock & Hamilton, 2008). Whereas, no male 20-km race walkers, three of the eight female 20-km race walkers and one participant in the control group presented T- and Z-scores below -1.0. Collectively this finding suggests that ultra-endurance athletes maybe at a higher risk of bone injury possibly because of large training volumes, inadequate nutrition and subsequent low energy availability (Mountjoy et al., 2018).

The following finding was that the 20-km male race walkers exhibited higher BUA values than the 20-km female race walkers but not SOS. This finding suggests the male 20-km race walkers posses greater trabecular bone tissue (Cepollaro et al., 1995).

However, the difference between sexes in BUA appears to not influence the overall calcaneal SI and as previously mentioned three of the eight female race walkers presented with calcaneal stiffness T- and Z-scores below -1.0. Thus, the values observed in this cohort of female race walkers appear to be variable and make it difficult to make definitive interpretations from this finding. Sex differences in bone density have been previously documented, where low BMD in females have been influenced due to body size, dietary intake that influence energy availability and hormonal factors (Hind, Truscott, & Evans, 2006). Other factors that may also contribute to these differences such as training intensity and ground reaction forces may play an important role, although no differences were found between training volumes in these race walking groups.

Lastly, some biomechanical values were associated with higher ultrasonographic values when assessing the race walkers as a population. All of these biomechanical variables were related to ground contact time related events and rate of loading. Greater time spent in ground contact of the gait cycle was associated with calcaneal stiffness variables whereas, greater time spent in the propulsion phase of ground contact was only associated with SOS and SI. These findings indicate that increased time in ground contact and more specifically during the propulsion sub-phase of ground contact are associated with greater calcaneal bone stiffness. Bone mineral density stimulation and bone strength are induced by mechanical forces produced by muscular and impact forces in runners (Schinkel-Ivy, Burkhart, & Andrews, 2013), as previously described in endurance runners (Hind et al., 2006).

Unlike in running, race walking implies higher contact times and subsequently vertical ground reaction force is more sustained when trying to walk at the same velocity as running. This possibly places a greater reliance on the lower limb muscle contraction than in running (Smith & Hanley, 2013) and may influence the calcaneal stiffness values observed in the race walkers with longer contact times of the gait cycle. Furthermore, the correlations found between BMD and the propulsive sub-phase of ground contact, could be attributed to the force placed on the calcaneus from the gastrocnemius and soleus during toe-off propulsion phase of gait (Hanley & Bissas, 2013). Moreover, the absence of knee flexion reduces ground reaction force attenuation through movement and increases muscles demand in facilitating it (Hanley & Bissas, 2017).

Also associated with higher BUA values was a greater initial loading rate. It appears that the greater the loading rate the greater the marker of bone mineral density in race walkers. This may be an indication of bone adaptation to higher loads experience by some race walkers. A further interpretation of this correlation may also suggest that greater vertical force development upon initial ground contact, could indicate higher exercise intensity or mechanical stimuli (Gast et al., 2013; Magkos et al., 2007). This could contribute to the greater BMD values found in the 20-km male race walkers, who perform higher velocity and subsequent intensive training regimes than 50-km male and 20-km female race walkers (Torre, Vernillo, Fiorella, Mauri, & Agnello, 2008).

Lastly, the outcome measures related to gait characteristics were only spatiotemporal in nature, and it may be that other biomechanical factors not reported here may be important determinants of bone density, in addition to muscular activation in the gastrocnemius and the tibialis anterior. Similarly, we acknowledge that bone mineral density assessment should be opened to other body areas and assessed with the use of dual-energy x-ray absorptiometry or quantitative computed tomography to provide a comprehensive overview of bone density and body composition in race walkers. Future research studying the relationships between bone density and biomechanical, nutritional and hormonal factors are thus warranted.

6.3 Race walking gait and its influence on race walking economy in World-Class race walkers

This study investigated the influence of spatiotemporal gait characteristics of race walking economy in world-class race walkers with an average personal best of 80.42 ± 2.13 min for 20 km (~ 4 minutes faster than the Olympic qualifying standard) and an average race walking economy of 241.30 ± 14.94 $ml \cdot kg^{-1} \cdot km^{-1}$. The first finding of this study was that race walking performance (according to their best 20-km race time), was positively associated with race walking economy at race pace, which implies that the fastest race walkers were more economical than the lesser performers. This association is in agreement with previous research in other endurance sports like distance running (Santos-Concejero et al., 2015), cycling (Faria et al., 2005) or cross-country skiing (Sandbakk & Holmberg, 2013) and further highlights the importance of movement efficiency in elite sport.

Previous research has hypothesised that certain biomechanical factors would be associated with greater movement efficiency in race walking, and that most economical race walkers may have distinct race walking patterns (Hanley & Bissas, 2017). In agreement with this hypothesis, we found significant relationships between race walking economy and ground contact characteristics (ground contact time, stance phase duration, midstance and propulsive sub-phases duration) as well as with flight time and swing phase duration. Specifically, in race walking step length is restricted because race walkers have to elude visible flight times to elude disqualification (IAAF, 2016). It has been reported that race walking judges cannot observe a loss of contact below the threshold of 0.040 s (Lee, Mellifont, Burkett, & James, 2013), although the real limit may be a bit higher as the fastest rate a human eye can retain an image is 16 Hz, or 0.06 s (Winter, 2005). This implies that current rules of observation by the judges are flawed as race walkers are provided a 'window' of non-perceptible flight times without the risk of disqualification. Angelis & Menchinelli (1992) analysed the progression of flight times in international race walkers at different speeds, reporting values of 0.04 ± 0.007 s at 14 $km \cdot h^{-1}$ (just in the limit of what is perceptible for the human eye). Similarly, Hanley, Bissas, & Drake (2011) observed flight times of 0.03 ± 0.01 s in competition. These results are in line with the values observed in this study (0.026 ± 0.007 s), suggesting that world-class race walkers can compete at fast speeds without a visible loss of contact with the ground. Interestingly, we observed positive correlations between flight time and race walking economy at 12 $km \cdot h^{-1}$ and at 14 $km \cdot h^{-1}$ and found that flight times increased when the speed was increased. Although we acknowledge that correlation does not always implies causation, this finding suggests that the most economical race walkers are those exhibiting shorter flight times at a given speed, resulting in a safer race walking technique in terms of risk of disqualification.

Previous studies on recreational and well-trained endurance runners (Paavolainen, Nummela, & Rusko, 1999; Santos-Concejero et al., 2014) have reported that shorter ground contact times are strongly associated with lower oxygen cost at speeds ranging from 12 $km \cdot h^{-1}$ to 23 $km \cdot h^{-1}$. Mechanistically, shorter ground contact times may reduce the duration of the braking phase during stance, which is usually associated with greater musculo-tendon stiffness and improved economy (Nummela et al., 2007; Paavolainen et al., 1999; Santos-Concejero et al., 2016). However, we found that longer ground contact times were related to a more efficient race walking economy at a given speed. Due to the rules that govern the sport (i.e. a straightened knee from the first contact with the ground until the vertical upright position), race walkers may need a longer stance phase and longer contact times to apply force to ground and move forward without losing speed. As a result, to increase their walking speeds, race walkers would be required to maximise step length and step length:heigh ratio to an optimal value that does not increase the aerobic demands (Morgan & Martin, 1986), neither violate the rules of the sport. The step lengths observed in this study are in accordance with those reported by (Hanley et al., 2011) in an elite 20-km competition (68.0 ± 3.7% *vs*. 68.1 ± 2.0% and 121 ± 0.7 cm *vs.* 120.5 ± 5.1 cm, respectively). Once the optimum step length is achieved, any speed increase would be dependent on increasing cadence (Cairns, Burdette, Pisciotta, & Simon, 1986). In this study, race walkers increased their cadence from 2.88 ± 0.1 steps·s^{-1} at 10 km·h^{-1} to 3.23 ± 0.14 steps·s^{-1} at a typical race-pace of 14 km·h^{-1} (12.22% increase). However, neither step length nor cadence were correlated with race walking economy or performance in this study.

It was observed that when race walking speed increased, the time spent in the initial contact sub-phase decreased by 19.1% (from 44.8 ± 6.1% at 10 km·h^{-1} to 36.2 ± 6.67% at 14 km·h^{-1}). This reduction in the initial contact sub-phase has been attributed to an increase in hip extension velocity before contact (Lafortune, Cochrane, & Wright, 1989). During the midstance sub-phase, race walkers must produce the energy to overcome the braking forces generated in the previous sub-phase and to prepare the body for acceleration during the propulsion sub-phase (Levine, Richards, & Whittle, 2012). This may explain the correlation found between race walking economy and midstance sub-phase at both 12 km·h^{-1} and at 14 km·h^{-1}. These findings agree with non peer-reviewed coaching opinion suggesting that the relation between gait sub-phases (initial contact, mid-stance and propulsive) may change the efficiency during race walking (Summers, 1991). Interestingly, although time spent in the propulsive sub-phase maybe beneficial in terms of race walking economy at slower speeds, it appears to be just a mechanical necessity as speed increases.

This is study was limited based on certain factors. These include a relatively small (n=21) and very specific and homogeneous sample, which makes generalisation of the obtained results to all race walkers difficult. Similarly, race walking economy was assessed on a motorised treadmill. It is known that the lack of air resistance results in a lower oxygen cost compared with exercising outdoors at the same speed (Mooses, Tippi, Mooses, Durussel & Mäestu, 2015). However, a 1% treadmill grade was chosen as previous research has reported that it accurately reflects the oxygen cost of exercising outdoors (Jones & Doust, 1996). In addition, spatiotemporal variables assessed in this study might vary from over-ground race walking when compared to treadmill race walking. Further, the outcome measures related to gait characteristics were only spatiotemporal in nature, and it may be that biomechanical factors related to stiffness and function of tendons, not reported here, are important determinants of race walking economy.

Future research studying neuromuscular activation in conjunction with ground reaction forces and 3-dimensional biomechanical analyses during over-ground race walking are thus warranted. These clinical, ecologically valid and in-depth measures may reveal additional answers for exceptional race walking performance in world-class race walkers and provide practical information for clinicians and coaches for ongoing management of elite race walking training programmes.

6.4 Biomechanical analysis of gait waveform data: differences between elite race walkers and runners

The main goal of this study was to compare the joint kinematics and kinetics of the gait waveforms in world-class race walkers and runners. Because of the rules that limit race walking gait, it was hypothesised that race walkers' kinetics and kinematics would differ from running at the same speed. Both spatiotemporal variables and analysis of waveform variables presented insightful results. The main finding was that differences were found in all three joints and planes throughout the gait cycle between the race walkers and runners. These differences are a consequence of the rules that race walkers are required to comply with (Rule 230.2) (IAAF, 2016) and are discussed in further detail below:

Spatiotemporal variables

Despite similar gait velocities, race walkers and runners exhibited contrasting values in spatiotemporal variables. Compared with runners, race walkers had higher ground contact times, in an attempt to avoid losing contact with the ground and to maintain a constant support leg on the ground. Whereas flight distances in elite race walkers have been previously observed to contribute to 13% of total step length, this factor has to be limited to avoid any visible loss of contact (Hanley & Bissas, 2017). Thus, because flight times are restricted, stride length remains a key factor in race walking performance (Hanley & Bissas, 2013; Hanley et al., 2013). Other notable modifications include higher cadences (due to restricted flight times) to maintain the same speed as running, with an added consequence of shorter swing phases during which to straighten the knee (on average 10% less of the gait cycle than in running). Moreover, the distribution and effectiveness of the use of sub-phases during the stance phase plays an important role in the displacement of the centre of mass (Cazzola et al., 2016; Pavei & La Torre, 2016; Preatoni et al., 2013). This was noticeable during the late stance sub-phase, which lasted longer in race walking than running, increasing the propulsion time required to maintain a similar velocity (Hanley et al., 2011).

Knee joint

The most distinct differences between running and race walking waveforms were observed in the sagittal plane of the hip, knee and ankle. In particular, reduced knee flexion was observed throughout stance in the race walkers when compared with the runners. Furthermore, the race walkers also exhibited knee hyperextension and delayed knee flexion during the propulsive phase of stance produced by the knee flexion-extension moment. An overall observation of the race walkers' knee flexion-extension gait cycle waveform illustrates a singular peak in knee flexion during the swing phase; notably, this is the absence of knee flexion during initial stance. The absence of this initial knee flexion peak in race walking has been suggested to be mechanically costlier than running at the same speed (Cronin et al., 2016; Marchetti et al., 1982). This phenomenon in running and normal walking during stance has been suggested to increase locomotion efficiency as a result of the energy-saving role of the Achilles tendon (Rogers, Whatman, Pearson, & Kilding, 2017). However, the flexion of the knee from the upright position to toe-off benefits the race walkers with a lower vertical oscillation of the body, consequently limiting flight time (Hanley & Bissas, 2017). This study clearly distinguishes for the first time the magnitude of difference in knee flexion during stance in elite race walkers and runners simultaneously. Furthermore, there is reduced knee flexion throughout swing during race walking compared with running. This might benefit race walkers in facilitating knee extension during late swing and help to reduce flight time, but with the subsequent disadvantage of increased energy cost from an increased lower limb moment of inertia (Smith & Hanley, 2013).

Hip Joint

The effect of having to achieve a straightened knee by initial contact and maintain it through mid-stance restricts the whole lower limb to one rigid lever. In response to this, the race walker adopts an exaggerated movement of the hip, which is one of the peculiar aspects of race walking (Murray, Guten, Mollinger, & Gardner, 1983; Pavei & La Torre, 2016). Compared with runners, a reduced hip flexion at initial ground contact was observed in the race walkers to avoid exaggerated over-striding in preventing greater braking forces (Padulo et al., 2013). In addition, higher variability in the frontal plane was showed by race walkers to effectively increase step length. As the pelvis moves forwards (creating an abduction of the hip) in conjunction with the leg, it creates a forward momentum and longer step length with a decrease in stride width (Knicker & Loch, 1990). During the stance phase and in response to the need to straighten the knee, race walkers rotate the hip obliquely to avoid vertical displacement of the body's centre of mass (Cairns et al., 1986; Pavei & La Torre, 2016). While the hip continues to extend until the first part of the swing phase in runners, race walkers begin flexing the hip before toe-off; this prevents the leg from falling behind and drives the leg forwards into swing (Hanley & Bissas, 2017). The larger hip abduction observed during swing appears to accommodate hip adduction during stance, as the stance leg is positioned below the body and the swing leg must move laterally outwards to pass it. The activation of the hip flexors and forward momentum created by pelvis rotation results in positive energy transfer, helping to the body to move over the straightened leg (Hoga et al., 2003). Subsequently, to ensure race walking gait is efficient and remains within the rules of competition, the hip has been suggested to be the predominant energy-generating joint in race walking gait (Hanley & Bissas, 2017).

Ankle Joint

In concordance with the other joints, ankle sagittal and frontal plane angles were limited in the race walkers when compared with the runners. To maintain a straight and stiff knee during initial contact, race walkers land with pronounced ankle dorsiflexion (Padulo et al., 2013), which is exacerbated as a consequence of knee hyperextension. In this study, the runners exhibited a neutral ankle angle during stance at initial ground contact that progressed into greater dorsiflexion at mid-stance and greater plantarflexion at toe-off. This allows runners to store and transfer energy using the Achilles tendon but the ankle position during race walking does not allow this. In this study there is a pronounced ankle dorsiflexion at initial ground contact that progresses directly into a neutral – plantarflexion and then a delayed and suppressed dorsiflexion before a reduced plantarflexion toe-off (Cronin et al., 2016). The possible absence of the elastic forces in the calf and Achilles tendon obliges the race walkers to generate a greater plantarflexion moment during late stance than running (Murray et al., 1983). Moreover, the reduced knee flexion that race walkers showed during the swing phase demands earlier and greater ankle dorsiflexion than in running. Whereas runners' ankle adduction and rotation are nearly neutral avoiding any wasting movement, race walkers have to ensure that the foot clears the ground and aids in a heel strike, requiring adduction of the ankle with an external rotation during swing phase (Hanley & Bissas, 2013; Pavei & La Torre, 2016; Ziv & Rotstein, 2009).

Vertical ground reaction forces

As the restricted range of motion during race walking does not allow the body to store and transfer energy as effectively as during running, it is observed that the lower magnitude of the vertical GRF in the race walkers appears to be linked to the entire kinematic chain. A greater initial loading rate, in addition to greater vertical GRF observed during mid-stance, was observed in the runners. This might be perhaps because of the ability to store and transfer energy during ground contact more efficiently using the Achilles tendon and other energy transfer strategies based on a spring-mass model (Rogers et al., 2017). By contrast, race walkers exhibited lower GRFs during mid-stance. This reduced and delayed GRF peak might first be explained by avoidance of high GRFs due to the observed overall restricted range of motion of the lower limb joint angles during stance. In addition, this might be explained by the contrasting gait patterns used by both groups of elite athletes to propel against the ground. Whereas race walkers move the knee from a hyperextended position to a flexed one during late stance (Hanley & Bissas, 2017), runners use a flexion-extension pattern in the mid-stance phase. Thus, the technical restrictions oblige race walkers to transfer the energy using an extension-flexion pattern, causing the biggest differences in the joint flexion moments between both groups.

The last finding of this study was that the runners exhibited a better economy than the race walkers at the same sub-maximal speed. This was evident despite athletes being matched for athletic ability with regard to IAAF performance scores and both groups comprising endurance athletes who compete over similar distances. However, physical differences were also found between groups that might be relevant to the specific event that they participate in and also influence transport cost (Stellingwerff, 2017). Interestingly, as running economy was expressed relative to body mass, the runners benefitted as a result of a reduced body mass (runners were 17% lighter than the race walkers); however, their smaller physiques might not be suited to race walking, where a greater stature is associated with longer step lengths (Hanley et al., 2013), and where muscle activation is greater (Cronin et al., 2016). For both running and race walking, mechanical work and metabolic demand were suggested to be a principal factor affecting efficiency of locomotion (Cavagna & Franzetti, 1981; Gomez-Ezeiza et al., 2018). Our results found significant differences between race walking and running gait patterns, suggesting that race walking is a less efficient movement as athletes are required to comply with IAAF Rule 230.2. Further research investigating the optimal biomechanics for efficient race walking economy is required to confirm this assumption.

It is important to note that we did not test these elite athletes at a faster velocity as result of overground laboratory space restrictions. This speed is still relevant as numerous biomechanical differences were still observed and would most probably be emphasised at higher velocities as previously documented in Kenyan athletes (Tam et al., 2016). Lastly, the use of the standard *PlugInGait* model was used to determine joint kinematics and kinetics. This model is acknowledged to provide highly variable transverse planes and limits our ability to effectively critique this plane (Tam et al.,2017); the use of a different model might elucidate differences that this model cannot reveal for this study. However, the entire waveform data from this model remains relevant because it is useful for understanding the gait changes and further interpretation of the differences between elite runners' and race walkers' gait patterns. Supplementary assessments of joint powers and work might yield further insightful results. The assessment of electromyography concomitantly with motion capture might also provide further information on the neuromuscular contributions necessary during race walking and its comparisons with running gait.

6.5 Muscle activation patterns correlate with race walking economy in elite race walkers: a waveform analysis.

The goal of this study was to explore muscle activation patterns over an entire gait cycle and its association with oxygen cost of race walking in elite race walkers. Interestingly, we have found some associations between oxygen cost of race walking and specific muscle group activation patterns at similar points of the gait cycle that may influence optimal race walking biomechanics.

Terminal swing and initial ground contact

Greater activation of gluteus maximus and biceps femoris at ground contact was associated with better race walking economy. Both posterior lower limb muscle relationships were found during late swing and continued into initial ground contact (96-100% and 0-6% of the gait cycle). This finding highlights the importance of proximal posterior muscle activation in contributing to oxygen cost of transport optimization, especially prior to and at initial ground contact. Previous research and our findings suggest these relationships activate in synchrony during this part of the gait cycle to prepare for ground contact and assist with joint stabilization and stiffness to lower oxygen cost of transport (Boyer & Nigg, 2004; Tam et al., 2016). Thus, these observed phenomena appear to be related to the management of ground reaction forces at ground contact.

Large loading forces are experienced at initial ground contact, and the management of these forces is key to efficient energy transfer and reduced metabolic demand during ground contact (Hamner, Seth, & Delp, 2010). Mechanisms to facilitate these forces appear to be associated with pre-activation (Hermens et al., 2000) during terminal swing (Tam et al., 2016) and consequent joint biomechanics that enable efficient gait (Tam et al., 2018). Thus, during initial ground contact, the biarticular muscle, biceps femoris appears to behave as a joint stabiliser for both the knee and hip, as similar findings have been found previously during running by Moore et al. (2014) and Heise et al. (1996). While the gluteus maximus extends the hip (Hanley & Bissas, 2013). The greater activation of gluteus maximus might reduce metabolic cost by optimizing neuromuscular control to assist efficient energy transfer (muscle tuning) (Boyer & Nigg, 2004) and joint movement (hip extension and stabilisation) (Heise et al., 1996). Understanding these specific neuromuscular profiles in relation to race walking economy may assist coaches to consider the importance of training motor control pathways when working with their athletes (Hanley & Bissas, 2016). By training these metabolic demands maybe be decreased by a reduction in co-activation through co-ordinate and selective activation profiles of antagonist-agonist muscles.

Midstance

Continuing from initial ground contact, associations between shank musculature and oxygen cost of race walking were found. Specifically, greater medial gastrocnemius and lower tibialis anterior activation were associated with favourable race walking economy. A similar finding has been previously observed in runners at 12 $km \cdot h^{-1}$ although this was over the entire ground contact phase (Tam et al, 2018). This study further details the temporal nature of this relationship that was found between 5-8% of the gait cycle in the medial gastrocnemius and 6-12% of the gait cycle in the tibialis anterior. This overlap of associations illustrates the importance of the posterior chain and agonist-antagonist co-ordination during gait (Kyröläinen et al., 2001). Considering a lower tibialis anterior activity was associated with better race walking economy and may be a feature of better technique as the activation of this muscle influence the stability of the ankle joint to optimally transition from initial ground contact to propulsion. Interestingly, higher activity has been suggested as a source of the shin pain frequently reported by race walkers (Hanley & Bissas, 2013; Francis, Richman, & Patterson, 1998) and thus excessive activation appears to be both uneconomical and possibly implicated with increased injury risk.

Further up the leg, greater rectus femoris activity was found to be favourable for metabolic cost before midstance (18-23% of the gait cycle). This finding, alongside previous other research could suggest that this biarticular muscle might act to mediate ground reaction forces through energy absorption through activation and simultaneous joint stabilisation of the knee and hip, allowing other structures of the lower limb to move in a way that improves energy transfer for locomotion (Heise et al., 1996; Hanley & Bissas, 2016).

However, during 35-41% of the gait cycle (post-midstance), lower rectus femoris activity was associated with better race walking economy. This is beneficial as increased activation of rectus femoris would possibly restrict gait kinematics, as this gait phase is associated with hip extension and knee flexion in order to shift the centre of mass.

Propulsion and swing

During terminal stance and early swing phases of race walking gait, a lower oxygen cost was associated with greater rectus femoris activation (Hanley & Bissas, 2016). The exertion of the hip flexor torques that are generated by a higher activation of the rectus femoris at this time might benefit the race walkers with more efficient energy usage (Hoga et al., 2003). Due to the dynamic coupling of the body, the greater activation of the rectus femoris during late stance may be more effective as it could influence both the trunk and support leg segments (Zajac & Gordon, 1989). This can be crucial given the contralateral stance leg's role functioning predominantly as a lever during midstance (Hanley & Bissas, 2013). Additionally, this strategy could benefit race walkers via a better horizontal force production, and consequently a lower vertical oscillation of the body (Hanley & Bissas, 2016). Thus, this finding suggests that the hip flexors play a substantial role in economical race walking by stabilizing and accelerating the lower limb through its bi-articular composition and proximal position.

Furthermore, the observation of a greater activation of the adductor magnus during early swing (43-50% of the gait cycle) is associated with higher race walking oxygen cost suggests that an excessive adduction of the hip is metabolically costly. Interestingly, this adduction of the hip is often observed in race walkers to increase step length and avoid visible loss of contact of the ground (Cairns et al., 1986), but these findings suggest that this might be counterproductive from a metabolic perspective. Notably, during this phase the role of posterior muscle activation shifts, and greater biceps femoris activity was found to be possibly detrimental to race walking economy. This is important as greater activation of the antagonist biceps femoris during this period of gait might obstruct forward propulsion during toe-off as it is predominantly performed by the hip flexors (Hoga et al., 2003).

Although the trials were performed on a treadmill and over ground, spatiotemporal data and walking velocity were found to be similar between conditions. Therefore, the comparisons can be made but one should not forget that differences between testing conditions do exist (surface, joint kinematics, belt vs. body speed etc.) but were minimized as much as possible. Further, understanding of the complex interaction between neuromuscular control and gait biomechanics could be further explored through analyses like functional data analysis or principal component analysis that could assist in collectively assessing features of such data on their impact on race walking economy.

7

CONCLUSIONS

"If I have seen further, it is by standing on the shoulders of Giants."

Isaac Newton

7. Conclusions

Anthropometry

The characterisation of the morphology of elite race walkers provides a reference values to assess an optimal body composition for an elite race walker, as well as providing reference values to improve talent identification. However, to ensure health, generate positive training adaptations and perform in the best conditions for each race walking event, coaches and nutritionists should control and manage body composition to complete the goals of each training phases during the season.

Bone Density

Race walkers exhibited differences in the ultrasonographic values at the calcaneus bone compared between sex and competitive specialization. These differences may be explained by the specificity of the training loads for the 50-km race walkers, resulting a negative relation between weekly training volume to BMD factors. Additionally, initial loading and greater contact time and propulsive energy production by the musculoskeletal system could make positive changes in BMD values in 20-km elite race walkers. Thus, it can be suggested that race walkers that endure very high training volumes are required to optimize their training load and energy availability to ensure healthy BMD values.

Race Walking economy

Race walking performance was positively associated with race walking economy, which implies that the fastest race walkers were more economical than the lesser performers. Interestingly, race walking economy was related to ground contact characteristics and swing time, which highlights the importance of race walking biomechanics for elite competitors in this sport.

Running vs. Race walking

Race walkers modify their gait pattern to maintain a velocity similar to runners whilst exhibiting restricted ranges of motion in the knee and ankle sagittal plane. Subsequently this resulted in larger kinematic changes in the hip and increased cadence and ground contact to maintain the same gait velocities. Thus, race walkers optimise their gait pattern from imposed gait contractions, resulting in a very specific and complex motor control task. Interestingly, these findings indicate that race walkers may require tailored technical, strength and conditioning training programmes specific to their athletic discipline race walking is evidently not running.

Neuromuscular patterns

The most economical race walkers possess a refined neuromuscular system that is optimally co-ordinated to reduce the metabolic demand throughout race walking gait. It appears that this is achieved through the modulation of muscle activity to effect efficient joint biomechanics. Also, the importance of proximal posterior muscle activation at terminal swing and initial ground contact is noted in efficient energy transfer (ground reaction force facilitation) and consequent optimal joint biomechanics (hip extension and stabilisation). Lastly, the role of the hip flexors during the propulsive phase and the early swing phase was found to be associated with oxygen cost of race walking, that is suggested to assist in coordinating the acceleration of the lower limb.

8

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"So many books, so little time."

Frank Zappa

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9

ADDENDUMS

"I am a greater believer in luck, and I find the harder I work the more I have of it."

Thomas Jefferson

Addendum 1

Different competition approaches in a world-class 50-km racewalker during an Olympic year.

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CASE REPORT
OTHER AREAS

Different competition approaches in a world-class 50-km racewalker during an Olympic year

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ABSTRACT

The aim of this case study was to compare the competition approaches for the Race Walking World Cup and the Olympic Games of a world-class 50-km racewalker. Total training volumes, intensity distribution, performance tests, high altitude stages and the evolution of his haematological values during the season were analysed. The last 12 weeks before the Race Walking World Cup (Approach 1) and the Olympic Games (Approach 2) were used for data analysis. Approach 1 was characterized by lower training volumes (791.7±192.8 min vs. 959.0±120.0 min ES=1.0, large effect) and a higher incidence of high intensity training (ES<0.8, large effect), than Approach 2. Approach 1 resulted in lower blood lactate values at set speeds, better haematological values and a better performance in the Race Walking World Cup than in the Olympic Games (3h47'30'' vs. 3h51'30''). According to the results of this analysis, it seems that a training strategy characterised by a higher incidence of high intensity training and lower volume of work may lead to superior training adaptations and performance in 50-km racewalking. This may help elite racewalkers and their coaches to achieve an optimum performance in their major goal competitions.

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Key words: Athletic exercise - Running - Athletic performance.

Men's 50-km racewalking is the longest race in the athletics programme of the Olympic Games and other major athletics championships.[1] This endurance event requires both the physical and technical ability to endure almost 4 hours of competition having a faster average racewalking speed than other racewalkers while maintaining a gait pattern in accordance with the rules (no visible loss of contact with the ground and straightened knee from the first contact to the vertical upright position).[2]

The annual plan of an elite racewalker is usually organised to excel in major Competitions such as the World Championships or the Olympic Games, with usually one or two major goals per season.[3] The competition dates and importance have direct implications for the periodisation of the annual training plan, as well as the adjustment of the volume, intensity and specificity of the training sessions.[4] Interestingly, current racewalking training guidelines recommend high training volumes at low intensities,[3] which have been reported to influence negatively the evolution of some haematological parameters with direct implications in performance such as Hb and RBC.[5] Similarly, current guidelines neglect the evidence in favour of the importance of high intensity training in endurance events.[6]

The aim of this case study was to analyse the training programme and the effects of different competition approaches (high intensity training and low work volumes *vs.* low intensity training and high work volumes) of a world-class 50-km racewalker during his Beijing 2008 Olympic campaign.

Case report

Methods

Participant

An elite racewalker (35 years old) with 10 years of training experience as a professional athlete (height: 1.78 m, body mass: 64.9 kg) agreed to participate in this study. His best performance was 3h41’20” in 50-km racewalking and he has placed TOP-10 in the last decade 5 times in European and World Championships. The Ethics Committee for Research on Human subjects of the University of the Basque Country (CEISH/GIEB) granted permission for this study. The featured racewalker gave written consent to use his detailed training load and test results data for this case study.

Training data

The detailed training load data used for this study were updated daily with the athlete’s feedback, who recorded the training and heart rate (HR) data personally in real-time using a heart rate monitor (Polar RS800, Kempele, Finland). Total training volumes are reported in terms of total work time (min), not reporting strength training as the racewalker just performed basic strength training sessions at the beginning of the season. Training loads are divided into five intensity zones to categorise the training load completed:[7] K1=55-75% of maximum heart rate (HRmax), K2 75-80% HRmax, K3 81-90% HRmax, K4 91-95% HRmax and K5 96-100% HRmax. These training zones were adjusted twice during the season on the basis of blood lactate concentrations and HR values recorded during an incremental racewalking test, which was performed 4 weeks before each major competition (Race Walking World Cup and the Olympic Games). This test consisted of 5 repetitions of 2000-m on the track, starting at 11.0 $km \cdot h^{-1}$ and where the walking-speed was increased by 1 $km \cdot h^{-1}$ with a minute recovery between each stage.[8]

Competition approaches

The racewalker started the Olympic campaign in October 2007 with a preparatory period of 8 weeks, which included running and general physical training. Thereafter, the racewalker spent 2 weeks at high altitude (1900 m, Benasque), where he did cross-country skiing as a transition to racewalking. The season was then divided into two macrocycles, the first one of 19 weeks until the Race Walking World Cup in Chevoskary (May 2008) and after two weeks rest, the second one of 14 weeks until the Beijing 2008 Olympic Games (August 2008). The competition approaches (last 12 weeks of each macrocycle: Approach 1 and Approach 2, respectively) were used for data analysis.

The racewalker completed a high-altitude training stage 6 weeks before each major competition. During the first competition approach, he spent a total of 4 consecutive weeks (2 weeks at 2250 m in Sierra Nevada and 2 weeks at 1900 m in Benasque), whereas during the second one, the racewalker completed a total of 6 consecutive weeks (2 weeks at 1800 m in Navacerrada, 2 weeks at 2250 m in Sierra Nevada and 2 weeks at 1800 m in Font Romeu). Apart from the Race Walking World Cup and the Olympic Games, the racewalker competed in other minor races, such as local and national championships, during the season. The priority of the races (from 1 to 3) are presented in Figure 1, being local races of 5 km and 10 km categorized as 3, the ational 20-km racewalking championships as 2 and the Race Walking World Cup and the Olympic Games as 1.

Blood analyses

Just before and after each high-altitude training stage, blood analyses were undertaken under the same conditions (*i.e.* hydration status) to track the changes in the racewalker’s haematological values (hemoglobin, hematocrit, ferritin and serum iron). During Approach 2, two weeks before starting the high altitude training stage and two weeks before descending to sea level, the racewalker used iron supplementation for two weeks each time (42 mg/per day).

Statistical analysis

The magnitude of differences or effect sizes (ES) and the 95% confidence intervals (95% CI) of the weekly work volume (min) and amount of training at different training zones (%) before the Race Walking World Cup and the Olympic Games were calculated according to Cohen’s d [9] and interpreted as small (>0.2 and <0.6), moderate (≥0.6 and <1.2), or large (≥1.2 and <2).

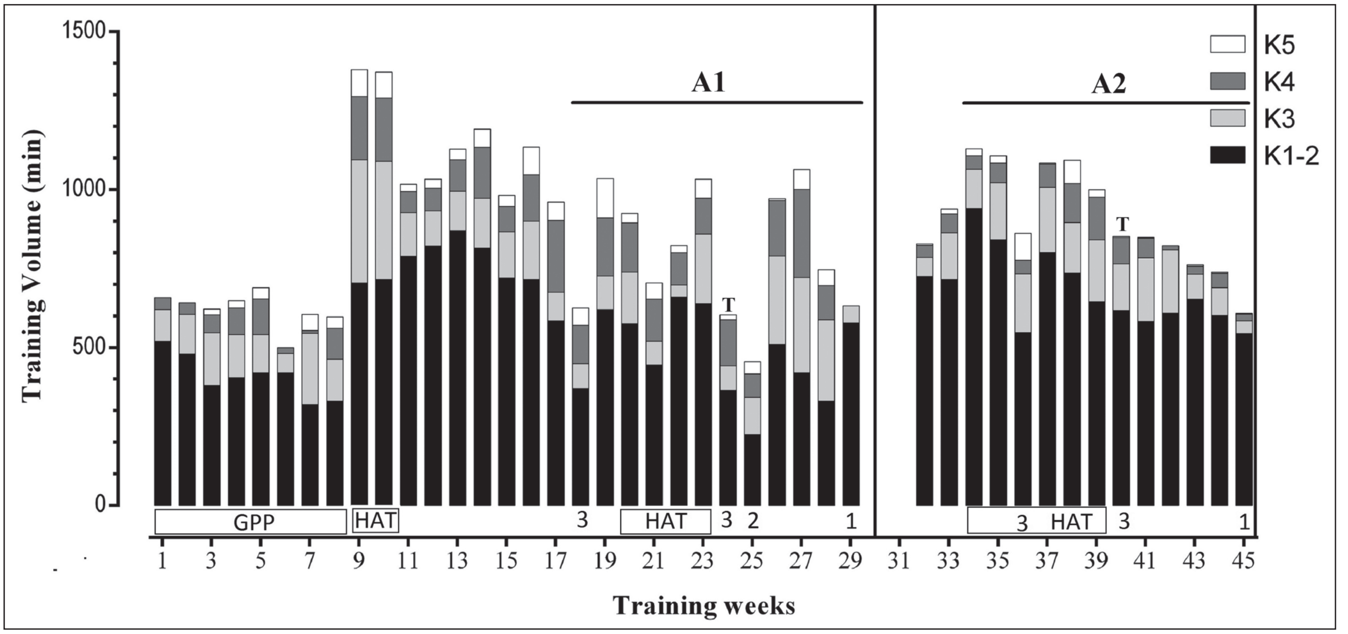

Figure 1.—Total training volume expressed in minutes with weekly training intensity zones distribution. The numbers represent the priority of the races during the season (1>2>3). The sub-zones represent the periods of General Physical Preparation (GPP) and High-Altitude Training Stages (HAT).Two approaching periods are expressed with A1 and A2. Testing weeks are represented with a T.

Results

Total training load

The weekly training volume and intensity distribution are depicted in Figure 1. The training data are based on 479 sessions divided in 45 weeks, with a total endurance work of 37457 minutes, of which 67.6% were performed at K1-2 intensities, 17.6% at K3, 11.0% at K4 and 3.8% at K5. Weekly training consisted of 832.4±287.8 minutes in 10±2 sessions.

Competition approaches

The first competition approach (last 12 weeks before the Race Walking World Cup, where the athlete finished in 4th position timed in 3h47’30”) had lower total training volume (9620 min *vs.* 10908 min, respectively) and weekly training volume (791.7±192.8 min *vs.* 959.0±120.0 min, respectively. ES=1.0, large effect, 95% CI from 0.16 to 1.86) than the second competition approach (last 12 weeks before the Olympic Games, where the racewalker finished in 13th position with 3h51’30”).

Training intensity zones distribution in each competition approach were 60.3±14.3% at K1-2, 18.0±9.6% at K3, 16.3±6.7% at K4 and 5.3±3.6% at K5 in the first competitive approach and 75.1±8.5%, 16.4±5.6%, 6.5±3.5%, 2.10±3.1%, in the second one (Figure 1). This implied a higher incidence of high intensity training (K4 and K5) (ES=1.84 & 1.84, respectively, large effect; 95% CI from 0.83 to 2.71 and 0.08 to 1.76) and a lower incidence of low intensity training (K1-2, ES=1.26, large effect; 95% CI from 0.34 to 2.09) in the first when compared to the second competition approach.

The incremental racewalking test results are presented in Figure 2. Four weeks before the Race Walking World Cup, the blood lactate concentration values at set racewalking speeds were lower (*i.e.* 1.9 $mmol \cdot L^{-1}$ *vs.* 2.8 $mmol \cdot L^{-1}$ at 13.5 $km \cdot h^{-1}$, indicative of race pace), than 4 weeks before the Olympic Games. In contrast, HR values were similar in both tests 4 weeks before each major competition (*i.e.* 152 *vs.* 150 $beats \cdot min^{-1}$ at 13.5 $km \cdot h^{-1}$, respectively) (Figure 2).

Haemoglobin concentration (16.2 *vs.* 15.12 $g \cdot dl^{-1}$; Figure 3A) and hematocrit (47.5 *vs.* 44.7%; Figure 3B) also showed a negative trend when comparing the values of the first and the second competition approaches (Figure

3). However, ferritin values (83 *vs.* 88 mg·mL^{-1}; Figure 3C) and serum iron concentration (81 *vs.* 73 µg·dl^{-1}; Figure 3D) were similar at the end of Approach 1 and 2.

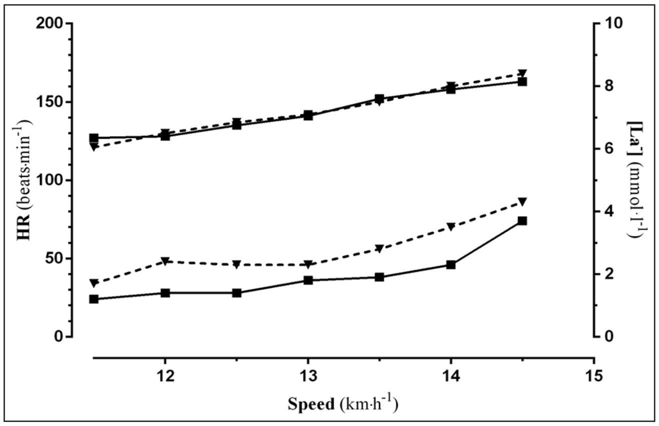

Figure 2.—Changes in blood lactate concentrations ([La$^-$]) and heart rate (HR) values during an incremental racewalking test consisting in 5x2000-m repetitions, 4 weeks before the Race Walking World Cup (■) and the Olympic Games (▲).

Discussion

The main finding of this study was that the training strategy used in Approach 1, which consisted in higher incidence of high intensities and lower volumes of work, resulted in a better performance, lower blood lactate concentrations and better haematological values than the training strategy followed in Approach 2 (higher volume of work and lower intensities).

The typical training programme of an elite 50-km racewalker is characterised by large volumes of work, mostly performed at low and moderate training intensities aiming for a peak performance at one or two major global competitions per season.[3] This was not the case for the racewalker featured in this study, as he followed two different competition approaches (12 weeks) before the Race Walking World Cup and the Olympic Games as coach's decision.

During the last 12 weeks of training before the Race Walking World Cup, the training plan was characterised by a smaller total and weekly volume of work (large ef-

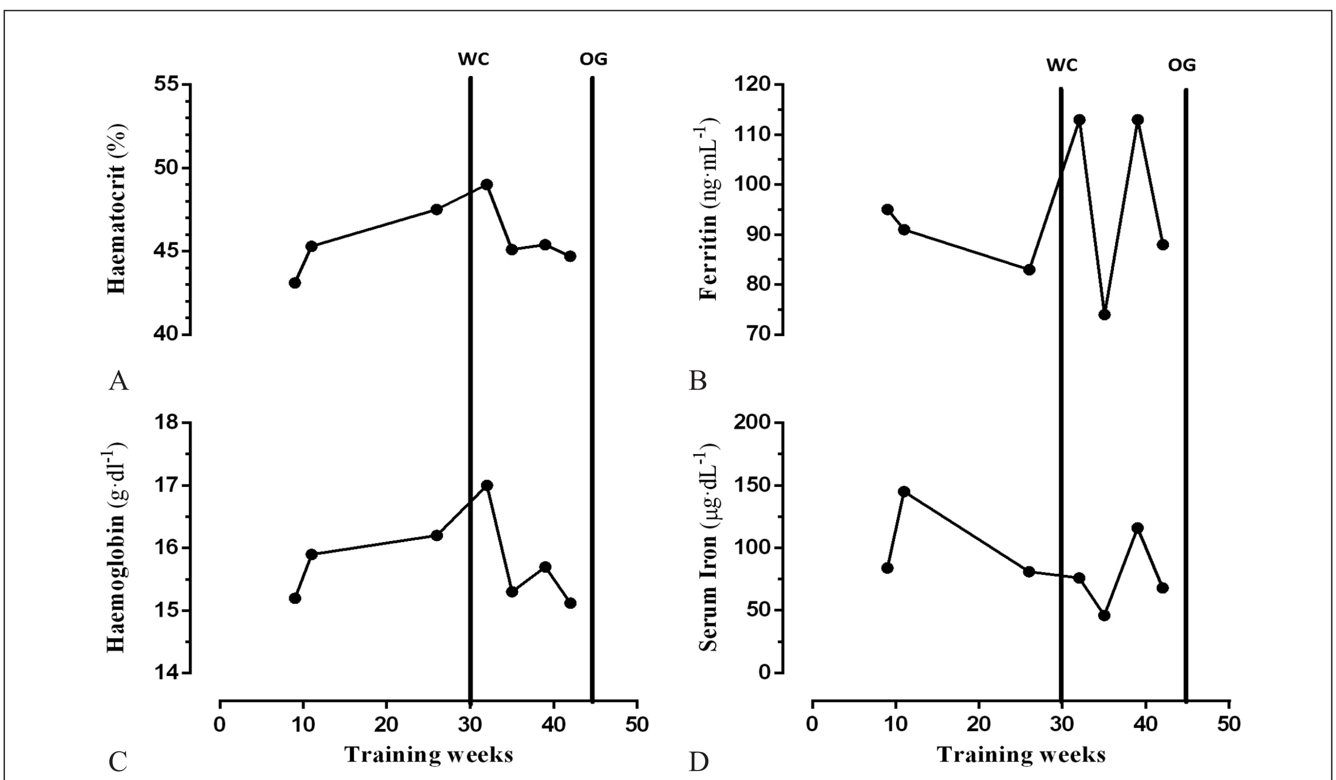

Figure 3.—The evolution of different haematological variables during the season: A) hemoglobin; B) hematocrit; C) ferritin; and D) serum iron. The lines indicate the Race Walking World Cup (WC, week 29) and the Olympic Games (OG, week 45).

fect) and higher intensity training (large effect) in comparison to the training plan before the Olympic Games (Figure 1).

This novel training strategy in Approach 1 contrasted with current racewalking training guidelines that are more focused on high training volumes at low intensities.[3]

The racewalker markedly reduced his training volume 6 weeks before the Race Walking World Cup for 2 weeks, and then completed 4 weeks with a high incidence of high intensity training (K3 - which is indicative of race pace- K4 and K5). In contrast, before the Olympic Games the racewalker followed a traditional longer linear approach with high incidence of low training intensities (K1-2) (Figure 1). Training at high intensities has been suggested to play a key role in inducing maximal physiological adaptations in highly trained athletes and to further enhance training-induced adaptations while athletes reduce their training volume before a major competition,[5] and more importantly, these adaptations can be elicited and maintained over the long term.[10] The training strategy followed during Approach 1 may therefore explain the lower blood lactate concentrations at race pace 4 weeks before the Race Walking World Cup when compared to the Olympic Games (Figure 2), although we acknowledge that the training regime the days before testing was not identical.

Despite the longer high altitude stage during Approach 2 when compared to Approach 1 (6 weeks *vs.* 4 weeks, respectively) and although the racewalker used iron supplementation during Approach 2, this did not result in better haematogical values on the contrary to the expected.[11, 12] The lack of erythropoietic response is usually attributed to illness or an injury blunt,[13] but this was not the case of the racewalker featured in this study. We explain the different haematological values recorded before each major competition by the different training strategies followed in Approach 1 and 2. Several studies have reported that consecutive high-volume training sessions, as was the case of the second competition approach (Figure 1), can result in decreased haematocrit and haemoglobin concentrations [11] and serum iron levels.[14] These worse hematological values, together with the different training intensity zone distribution in the first and second competition approaches, may therefore partially explain the racewalker's impaired performance in the 50-km racewalking event in the Olympic Games.

Conclusions

In summary, according to the results of this analysis, it seems that a training strategy characterised by a higher incidence of high intensity training and low volume of work may lead to superior training adaptations and performance in 50-km racewalking when compared to current guidelines consisting in high volume at low training intensities. This may help elite racewalkers and their coaches to achieve an optimum performance in their major goal competitions.

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Addendum 2

Anthropometric characteristics of top-class Olympic racewalkers.

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ORIGINAL ARTICLE

SEZIONE

Anthropometric characteristics of top-class Olympic race walkers

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ABSTRACT

BACKGROUND: Typical training programmes in elite race walkers involve high training volumes at low and moderate intensities, which have been reported to induce functional and structural adaptations at an anthropometric level. Since anthropometrical variables are closely related to movement efficiency and performance in endurance events, the aim of this study was to describe the anthropometric profile of world-class race walkers.

METHODS: Twenty-nine world-class race walkers (21 men and 8 women) participated in this study. Anthropometric characteristics, including height, body mass, eight skinfolds, five girths and four bone breadths were measured. Body composition, somatotype, somatotype dispersion mean, somatotype attitudinal mean and height to weight ratio, as well as skinfolds extremity to trunk ratio were also calculated

RESULTS: Mean height, body mass and body mass index were 177.1±7.1 cm, 66.4±5.8 kg, and 21.2±1.3 kg·m² for men and 165.6±4.5 cm, 53.6±3.7 kg, and 19.6±1.6 kg· m² for women, respectively. Women presented greater body fat content (6.7±0.6 *vs.* 12.2±0.8%; very large effect), less muscle mass (65.6±4.6 *vs.* 61.6±2.6 kg; large effect), and were more endomorphic (large effect) than men. Men specialists in 20-km showed greater muscle mass (66.7±4.9 *vs.* 64.4±4.3 kg; moderate effect), and slightly higher skinfolds, girths, body fat content and were more mesomorphic than 50-km specialists (moderate effect).

CONCLUSIONS: The present study expands the limited knowledge on the anthropometric characteristics and somatotype elements of elite top-class race walkers. The characterisation of the morphology of elite race walkers provides coaches a reference values to control the training development of the race walker, as well as providing reference values to improve talent identification.

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Key words: Walking - Anthropometry - Adipose tissue - Somatotypes - Athletes.

Race walking is an athletic event where athletes compete over distances of 20 kilometres and 50 kilometres. The peculiar gait employed in race walking is a consequence of the rules that govern this sport, as judges disqualify competitors who display a visible loss of contact with the ground or a bent knee from first contact until the vertical upright position.[1] Race walking places special emphasis on technical ability and endurance capacity,[2] as success in endurance events has previously been associated to certain physiological parameters,[3, 4] including: 1) a greater cardiac output; 2) higher capacity to uptake and delivery oxygen to active muscles; 3) a faster lactate threshold; and 4) a lower oxygen cost of transport.

Numerous studies have found relationships between endurance performance and anthropometrical parameters, based on the proportional relationships between metabolic cost and body mass.[5] The most important physiological metrics to excel in endurance events are dependent on body mass (*i.e.* VO_{2max} in mL/kg/min, running economy in mL/kg/km).[6] Thus, the body composition is known to influence an athlete's potential within a sport such as running,[7] cycling[8] and skiing.[9] For instance, Teunissen *et al.*

showed that the 74% of the total metabolic cost of running is generated by the support of the body weight.[10]

As race walking is an endurance event based on the forward propulsion of the body, a reduced body mass might be a good strategy to improve performance.[6] However, too low body mass may be a consequence of muscle mass loss,[11] low bone mineral density,[12] sickness[13] and injury,[12] which would ultimately affect performance outcomes by decreasing the ability to enhance training adaptations and to generate optimal power and speed.[6]

Race walkers may improve their anthropometrical profile as an strategy to ensure health, generate positive training adaptations and perform in the best conditions, Many endurance athletes use different nutritional strategies to optimise their body composition[14] and specific training regimes have also been reported to induce specific functional and structural adaptations, including changes in anthropometrical variables such as body mass and the sum of skinfolds.[7] Elite race walking training regimes are typically characterised by high training volumes at low and moderate intensities, which may result in certain specific functional and structural adaptations.[15] Although some studies have previously reported that well-trained race walkers have similar anthropometric characteristics to other endurance athletes,[16] the anthropometrical profiles of elite race walkers of different distances are yet to be explored.

Thus, the aim of this study was to describe and compare the anthropometric profile of world-class female and male race walkers and their respective distance specialisation (20-km and 50-km). Secondly, this study aimed to establish reference values for athlete selection, talent identification and training programme development in race walking.

Materials and methods

Participants

Twenty-nine international elite race walkers from Spain, Canada, Australia, France, Mexico, Sweden, Ireland and England agreed to participate in this study. All race walkers met the Olympic Entry Standard for Games of the XXXI Olympiad taking place in Rio de Janeiro 2016 (1:24:00 for men and 1:30:00 for women in 20-km and 4:06:00 in 50-km for men). Our sample also included the current World and Olympic champions for men over both 20-km and 50-km. Participants were tested during their training stages in Europe, in preparation for target International Amateur Athletics Federations' (IAAF) Permited Race walking meetings (*i.e.* XXX Gran Premio Cantones de La Coruña), were informed about all the tests and possible risks involved and provided written informed consent before testing. The Ethics Committee for Research on Human subjects of the University of the Basque Country (CEISH/GIEB) granted permission for this study (REF. 66/2015).

Data collection

Anthropometric characteristics were measured in a resting state by an accredited anthropometrist following the standardised techniques adopted by the International Society for the Advancement of Kinanthropometry (ISAK). All variables, except body mass and height, were measured on the right side of the body.

Height and body mass were measured in running shorts to the nearest 0.1 cm and 0.1 kg using a portable stadiometer (Seca, Hamburg, Germany) and digital scale (Tanita Corporation, Tokyo, Japan), respectively. Eight body skinfolds (triceps, subscapular, biceps, iliac crest, supraspinale, abdominal, front thigh and medial calf) were measured to the nearest 0.2 cm using a Harpenden skinfold caliper (British Indicators Ltd, St Albans, UK) and the sum of the eight skinfolds was calculated. Bone breadths and segmental girths were measured by a small bone sliding caliper (Rosscraft Innovations Inc, Vancouver, Canada) and a retractable measuring tape (Cooper Industries, Sparks, NV, USA), respectively. Girths were corrected at the sites where the skinfold and girth measurements coincided (upper arm, thigh and calf) using the formula proposed by Jelliffe *et al.*[17] All anthropometric equipment was calibrated before the assessment period, with additional checks made against certified calibration weights and rods. Every measure was performed twice, and a third measure was taken when the difference was >5% for skinfolds or >1% for other anthropometric variables.

Body fat content was calculated as proposed by Yuhasz,[18] whereas the muscle mass was calculated according to equation proposed by Matiegka.[19] Health-Carter equations were used to estimate the somatotype, determining the relative fatness (endomorphy), musculoskeletal robustness (mesomorphy) and linearity or slenderness (ectomorphy) using a score of 0.5-2.5 for low, 3.0-5.0 moderate, 5.5-7.0 high, and ≥7.5 very high.[20]

Statistical analysis

All values are expressed as mean±standard deviation (SD). Statistical analyses of data were performed using the Statistical Package for the Social Sciences 21.0 software package (IBM Corp, Armonk, NY, USA). Data were screened for normality of distribution and homogeneity of variances using a Shapiro-Wilk Normality Test and a Levene's test, respectively. One-way ANOVA was used to compare anthropometrical characteristics between race walkers of different sex and event. The magnitude of differences or effect sizes (ES) were calculated according to Cohen's *d* [21] and interpreted as small (>0.2 and <0.6), moderate (≥0.6 and <1.2) and large (≥1.2 and <2) according to the scale proposed by Hopkins.[22] Significance for all analyses was set at P<0.05.

Results

The average 20-km race walking time of the participants was 80.79±2.11 min (CV=2.6%) and 90.93±2.81 min (CV=3.1%) for men and women, respectively, indicating that the sample was homogenous from a performance point of view.

All the absolute anthropometric characteristics are presented in Table I. In men, we found no significant differences in height, body mass, fat percentage or muscle mass between 50-km and 20-km specialists. However, male 50-km race walkers were significantly older than those competing in 20-km (ES=0.86 moderate effect, P=0.01) and presented lower sum of skinfolds (ES=0.78 moderate, P=0.02).

When comparing 20-km men and women specialists, we observed significant differences in height (ES=0.77 moderate, P<0.001), body mass (ES=0.83 moderate effect, P<0.001), sum of skinfold (ES=0.89 moderate effect, P<0.001), body fat content (ES=0.97 moderate, P<0.001) and muscle mass (ES=0.84 moderate effect, P<0.001).

Figure 1 depicts a graphical description of individual values and the mean of the sample of somatotype values for both male and female race walkers. Again, we found no significant differences between the somatotype classification of the three groups analysed. Even though all groups presented a balanced mesomorph-ectomorph somatotype, the figure exhibits a specific somatotype profile related to the position of the mean values for each event group. In men, 20-km race walkers presented higher mesomorphism values than 50-km race walkers, with a tendency towards more muscular physique when compared to the linearity presented by the 50-km race walkers. On the other hand, 20-km female race walkers scored higher endomorphic values than men.

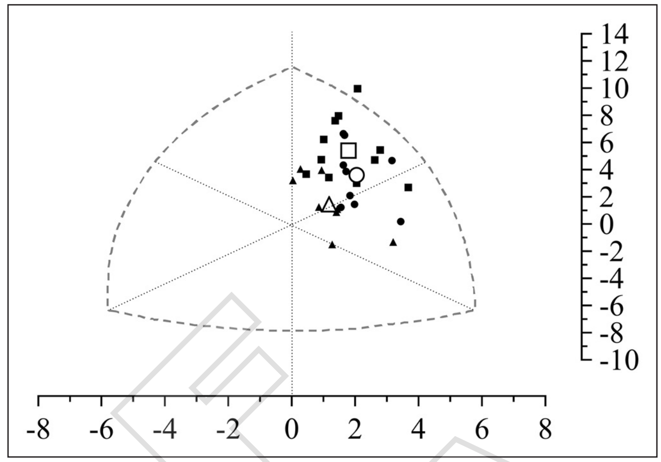

Figure 1.—Somatotype distribution of elite race walkers according to sex and competitive event. Squares: 20-km male race walkers. Triangles: 20-km women race walkers. Circles: 50-km male race walkers. The biggest icons represent the mean value of each event participants.

Table I.—*Anthropometrical characteristics of elite racewalkers.*

	20-km men (N.=11) Mean±SD	50-km men (N.=10) Mean±SD	20-km women (N.=8) Mean±SD
Age (years)	24.9±3.2†	28.5±4.9	22.5±2.8
Height (cm)	177.5±5.4	176.6±6.9	165.5±4.4*
Mass (kg)	67.8±5.5	65.0±3.2	53.6±3.7*
∑ 8 skinfold (mm)	49.9±3.9†	45.6±3.5	71.9±6.9*
Body fat (%)	6.8±0.2	6.4±0.3	12.2±0.8*
Muscle mass (kg)	38.0±2.9	36.5±3.3	30.8±1.3*
Skinfolds (mm)			
Biceps	2.8±0.3	2.8±0.5	5.1±2.8
Subscapular	7.2±0.7	7.0±1.3	7.2±0.9
Triceps	5.7±1.5	6.0±1.7	10.7±1.2
Iliac crest	7.6±1.0	7.1±1.0	10.8±2.9
Supraspinale	6.9±0.82	6.1±1.4	8.7±2.3
Abdominal	7.5±0.9	7.0±1.3	9.3±2.0
Front thigh	7.7±1.0	7.5±2.0	12.7±4.1
Medial calf	4.35±0.9	4.4±0.9	7.2±1.3
Breadths (cm)			
Wrist	4.9±0.7	4.8±0.6	4.2±0.6
Humerus	6.1±0.6	5.9±0.4	5.3±0.6
Femur	8.9±0.8	8.6±0.9	8.0±0.7
Ankle	6.10±0.6	6.0±0.5	5.5±0.7
Girths (cm)			
Relaxed arm	28.0±1.2	27.6±1.8	24.5±1.5
Flexed arm	29.4±1.3	28.7±1.6	25.3±1.4
Waist	73.6±2.4	73.7±3.05	66.0±2.7
Hip	91.3±2.3	90.0±4.3	87.0±8.1
Mid-Thigh	48.9±2.2	48.2±2.3	47.4±2.7
Calf	36.1±1.7	35.2±1.3	34.1±1.7

Values are mean±SD. Significant difference on main characteristics (P<0.05): *20-km women *vs.* 20-km men group and †20-km men *vs.* 50-km men group.
CV: coefficient of variation; ∑ 8 skinfolds: biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh and medial calf.

Discussion

The main finding of this study was that sex differences were found for all key anthropometrical characteristics required to excel in endurance events. In addition, males competing in the 50- and 20-km race walking events also presented differences in certain variables. These results suggest that unique anthropometric profiles are suited to each event (Table I). Previous research has shown the positive influence of certain anthropometrical characteristics on endurance performance.[6-9] Of these, the most used anthropometrical parameter in endurance athletes is the sum of skinfolds, often reported as an important predictor of endurance performance.[23] Previous studies analysing elite endurance athletes have reported low skinfold thickness and body fat content, which is in agreement with the results of this study (Table I).[6-9] For instance, a lower sum of skinfolds was found in the 50-km male racewalkers when compared to their 20-km male counterparts. Similarly, Legaz-Arrese *et al.* found lower skinfold thickness in marathon runners than athletes competing over shorter distances.[24] This lower sum of skinfold is representative of a reduced subcutaneous fat and gross mass, which may consequently reduce the muscular effort required to maintain the same walking intensity.[10] Interestingly, a lower sum of skinfolds and body fat content was found in male race walkers when compared to female walkers. This is in agreement with other studies describing sex differences in multiple athletic disciplines.[25]

It is known that endurance training regimes result in specific anthropometric adaptations.[26] To our best knowledge, there is a lack of longitudinal data describing anthropometrical changes associated with training regimes of elite race walkers. However, this can be inferred taking into account the seasonal training load of elite race walkers.[15] It has been reported that the training regime of an elite race walker consists of very high training volumes at low intensities, divided into phases where training load is variable (volume/intensity). Specifically, Knechtle *et al.* showed that weekly training volumes are associated to lower sum of skinfolds and body fat percentages.[26] These changes, and other factors like injuries, illnesses, recovery phases, altitude training camps etc. may also contribute to changes in body composition during the season.[11] Considering the years of continuous training spent by athletes in a high-performance environment, certain anthropometric adaptations during the whole period are expected.

With the aim of reducing body fat mass, some endurance athletes use nutritional interventions.[14] However, a reduction of energy availability may concomitantly be associated with a loss of muscle mass,[11] which may result in a reduced capacity to produce optimal muscle-power.[6] In this study, a greater muscle mass was found in both 20- and 50-km elite race walkers (38.0±2.9 and 36.5±3.3 kg) when compared to elite endurance athletes from other studies such as Kenyan runners (33.2 kg, ES=0.76, moderate effect)[27] or European runners.[28] Higher muscle mass in the race walkers may be explained by the greater muscle demand and effort needed to maintain the race-walking gait patterns.[29] Unlike running, the rules that govern race walking force the race walker to limit the gait to a less efficient pattern. Specially, the lack of knee flexion that does occur during stance phase has been shown to result in a reduced energy-saving role of the Achilles tendon, in addition to higher muscle effort done by the use of: 1) longer propulsive phases; 2) higher stride frequencies; 3) greater action of the upper-body; making race walking mechanically more costly than running at the same speed.[30, 31]

In this study, the somatotype categorisation in male and female race walkers was compared to assess morphology according to the relative contribution of three fundamental elements: mesomorphy, ectomorphy and endomorphy. A study conducted by Vernillo[29] reported the ectomorphic character that showed elite Kenyan marathon runners, related to a relative linearity and long-line body types. However, the results of this study show that elite race walkers exhibited a balanced mesomorph-ectomorph somatotype dimension (Figure 1). This morphological body-type is characterised by an athletically balanced element of a longi-linear athlete with well-developed muscles. Although all groups in this study presented a balanced mesomorph-ectomorph somatotype, distance specialised group (20-km *vs*. 50-km) exhibited a specific somatotype-rating trend related to the values of each somatotype category (Figure 1). These anthropometrical and morphological differences may be a result of the different training approaches from the different competitive distances. The higher training volumes at low intensities employed by the 50-km race walkers may rely on the use of fat metabolism and imply a reduced energy availability.[12] This may induce adaptations in lower sum of skinfolds, favouring a more ectomorphic somatotype profile. In contrast, race walkers competing over 20-km train at a higher intensity and speed,[32] resulting in slightly greater muscle mass values and more mesomorphic profiles.

This study faced several limitations. The first limitation of this study is the error in anthropometric manual measurement, the technique used, the equipment, the formula used, and the site location, as all these factors can affect the results. However, since the anthropometrical measurements were performed by an accredited anthropometrist following standardised techniques, we believe that the measurement error was negligible. In the future, the use of dual energy X-ray absorptiometry (DXA) could most appropriately assess the anthropometrical characteristics of elite race walkers.[33]

Conclusions

The present study expands the limited knowledge on the anthropometric characteristics and somatotype elements of elite top-class race walkers in each competitive distance events. The characterisation of the morphology of elite race walkers provides a reference values to assess an optimal body composition for an elite race walker, as well as providing reference values to improve talent identification. However, to ensure health, generate positive training adaptations and perform in the best conditions for each race-walking event, coaches and nutritionists should control and manage body composition to complete the goals of each training phases during the season.

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Addendum 3

The influence of racewalking on the calcaneal bone density status in world-class racewalkers.

CALCANEAL BONE DENSITY IN WORLD-CLASS RACE WALKERS: BIOMECHANICAL AND TRAINING DISTANCE CONSIDERATIONS

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CALCANEAL BONE DENSITY IN WORLD-CLASS RACE WALKERS: BIOMECHANICAL AND TRAINING DISTANCE CONSIDERATIONS

ABSTRACT

Background: Elite race walkers can walk up to 1000 minutes each week during the athletic season, which may dramatically affect the skeletal system through repetitive loading. Assessing the bone density of elite race walkers will improve our understanding of race walking's relationship with health, injury risk and performance.

Methods: Twenty-four elite race walkers and 16 healthy controls participated in this study. BMD was assessed with ultrasonography of the calcaneus using speed of sound (SOS), broadband ultrasound attenuation (BUA), stiffness index (SI), Z- and T-scores. Gait variables and GRF were also determined in the race walkers.

Results: The 20-km race walkers presented higher SOS ($p=0.032$) and SI ($p=0.041$) values than the 50-km male race walkers, who had lower mean T- and Z-scores ($p=0.007$; $p=0.003$). In addition, BUA differed between male and female 20-km race walkers ($p=0.049$). Greater training load and the initial loading rate was associated with BUA ($p=0.022$; $p=0.049$). Greater time spent in ground contact and propulsive phase, were associated with higher SOS and SI ($p=0.003$; $p=0.004$ and $p=0.004$; $p=0.014$, respectively).

Conclusions: The specificity of the training may explain the differences observed on the BMD on race walkers. Initial loading and the propulsive energy production could positively change the BMD in race walkers. Additionally, race walkers may be required to optimize their training load and energy availability to ensure healthy BMD.

Key words: bone stiffness; ground contact; injury risk; training; elite; load

1. INTRODUCTION

Race walking is a unique athletic event included in the Olympic Games and other major athletic championships, where participants compete over 20-km and 50-km. Elite race walkers display not only a great endurance capacity, but also great technical ability as they must adhere to the rules that govern this discipline: no visible loss of contact with the ground and a straightened knee from the first contact until the vertical upright position [1]. This rule results in a peculiar gait pattern that enforces a definite heel-strike and extended knee at initial ground contact [2].

It has also been reported that elite race walkers can walk up to 1000 minutes each week during the athletic season [3], which may dramatically affect the skeletal system through repetitive loading [4]. Bone stimulation derived from high muscular forces and high impact forces has been reported to promote osteogenesis [5] and the greater the forces, the greater the osteogenesis effect [6]. It is known that sports linked to direct actions of gravitational forces, such as running, generate higher osteogenesis than sports like swimming or rowing [7]. Similarly, animal studies using external loads have found higher bone osteogenesis by applying high magnitude strains at a high rate and relatively lower strain cycle [8]. However, there is no agreement linking bone mineral density (BMD) to training volume as some studies have found increased BMD in bones associated with impact loading [9], whereas other studies associated an increased training volume and running distances with lower bone densities [10].

Thus, it appears that the site of loading will likely influence bone density most proximal to load application. Despite this, many factors also have the potential to negatively affect bone density in athletes with high training volumes: low calcium and D vitamin intake [11], energy deficit [12], low body fat [4] and low testosterone levels [13]. In fact, even elite runners have been found to present with low lumbar spine bone density values due to low energy availability [9] and even stress fracture [14]. This suggests a risk in elite race walkers who are exposed to both high training loads and constrained gait patterns and loading.

Bone health has been extensively assessed in sedentary populations determining bone formation and turnover [15]. Similarly, a few studies on bone health in elite athletes have also been published across various sporting disciplines [7], including skiers [16], football players [17] and endurance runners [9,10]. These studies associated BMD with injuries [18], training volumes [4], sex or age [19]. To date, only two studies assessing bone characteristics in master race walkers have been conducted [20] [21], although bone characteristics in elite race walkers have yet to be explored.

Recently, Lara et al. [6] reported calcaneal bone stiffness, a cost effective and portable method of determining bone density, in a cohort of amateur recreational runners. They found that calcaneal stiffness was higher in the endurance runners than sedentary controls. In addition, greater bone stiffness values were observed in marathon runners than their half-marathon and shorter 10-km counterparts. On the contrary, Gast et al. [22] found an inverse association between competitive distance with BMD in short-, middle- and long-distance masters athletes. Whether or not this is exhibited in younger elite race walkers is of interest as their training volume and unique gait pattern may expose the body to different external and internal loads [23] and subsequent influence on bone density than runners. Calcaneal bone stiffness is of interest as it is the first bone exposed to the external ground reaction force at ground contact, and is also influenced by internal loading produced by the contractions of the gastrocnemius and tibialis anterior [24]. The question arises whether any relationship between bone density, competitive distance, training volume, sex and biomechanics exist in elite race walkers.

Subsequently, assessing the bone density of elite race walkers will improve our understanding of race walking's relationship with health, injury risk and performance. Thus, this study aimed to describe and compare markers of bone density in elite male and female race walkers. In addition, this study aimed to determine relationships between spatiotemporal and ground reaction variables characteristics of the gait cycle that may influence the bone density variables.

2. MATERIAL AND METHODS

2.1 Participants

Twenty-four world-class race walkers (16 males and 8 females) volunteered to participate in this study. All race walkers were of Olympic Entry Standard for Rio de Janeiro 2016 (1:24:00 for men & 1:34:00 for women in 20-km and 4:06:00 in 50-km for men). Additionally, a convenience sample of sixteen (8 males and 8 females) apparently healthy male and female active students were recruited as a comparative cohort for calcaneal stiffness measures. Participants were tested during training camps in Spain, whilst they were in Europe for target IAAF Permit Race Walking meetings (i.e. XXX Gran Premio Cantones de La Coruña) before to the Rio de Janeiro 2016. Participants provided written informed consent after they were informed about all tests and possible risks involved. The Ethics Committee for Research on Human subjects of the University of the Basque Country (CEISH/GIEB) granted permission for this study (Ref. 2015/053).

2.2 Design and protocol

The study was performed in a resting state without any training or physical activity 24 hours before the measurement of the calcaneus stiffness. In addition, race walkers provided information regarding training habits and previous medical conditions and injuries. For descriptive purpose, anthropometrical characteristics were measured following the standardised techniques adopted by the International Society for the Advancement of Kinanthropometry [25]

2.2.1 Calcaneal density assessment. An ultrasonographic bone scanner (Achilles, General Electric Healthcare-Lunar, WI, USA) was used to perform an assessment of the calcaneus of the right foot [6]. This scanner consisted of a control box with a heel water bath and two transducers placed opposite each other on either side of the water bath. One of these transducers emitted ultrasound signals through the water bath with the heel in it. whilst the other received the signals emitted. All signal parameters were digitised and further analysed for biological interpretation. Recent investigations have shown that quantitative ultrasound can accurately determine the exercise induced changes in bone status [15]. The bone scanner used as found to be both valid and reliable in prior studies, with a coefficient of variation of 0.47%, 2.6% and 1.6% for speed of sound (SOS), for the broadband ultrasound attenuation (BUA) and the calcaneal stiffness index (SI), respectively [26].

During this assessment race walkers were seated with their right bare foot placed in the water bath. Subsequently, expandable membranes were filled with warm water and isopropyl alcohol was used to assist coupling between the heel and the membranes, consequently eliminating air spaces. Signals recorded during each assessment by the bone scanner used to determine bone density were the speed of sound and the broadband ultrasound attenuation. While SOS assesses the elastic resistance of the bone, which is related to mineral and protein contents, the loss of ultrasound energy occurred by absorption or dispersion was assessed by the BUA, which is related to the bone density [26]. The calcaneal stiffness index (SI) was calculated by the combination of SOS and BUA related to participant age as follows [6]:

$$SI = (0.67 \cdot BUA + 0.28 \cdot SOS) – 420$$

T- and Z-scores for calcaneus stiffness were calculated for each ultrasonographic measurement using the predetermined reference values used by the manufacturer's software. The individual T- and Z-score represents the difference between the participant's value for calcaneus stiffness and the mean value for a population of young adults of the same sex with peak bone mass and the difference between the participant's value for calcaneal stiffness and the value of a sex- and age-adjusted population, respectively [22].

2.2.2 Spatiotemporal variables. The spatiotemporal assessment was conducted during a treadmill test using an optical measurement system (Optojump-next, Microgate, Bolzano, Italy). The values between the 2nd and 3rd min of the race walking stage corresponding to 12 $km \cdot h^{-1}$ were averaged to analyse a stable gait data. Gait cycle characteristics determined were ground contact time, swing time, step length, cadence and the percentage of the stance phase at which the different sub-phases occurs (initial contact, midstance and propulsion). During stance, the initial contact sub-phase corresponds to the time from initial ground contact to foot flat; the midstance sub-phase from foot flat to initial take off and the propulsive sub-phase from initial take off to toe off.

2.2.3 Ground reaction forces. Ground reaction force (GRF) data were collected at 2000 Hz, using a 900 × 600 mm force platform (AMTI, Watertown, MA, USA). Race walkers completed four trials at the same speed (12 $km \cdot h^{-1}$) on a 30-m indoor laboratory track. Trials were accepted if the speed was within ± 4% of target speed and when there was no visual evidence of athletes targeting the force platform. Force platform data were filtered using a low-pass fourth-order Butterworth filter with a cut-off frequency at 100 Hz. For each trial, the participants right limb was analysed. GRF data were normalized to bodyweight (BW). Peak vertical GRF as well as initial loading rate were determined as previously described by Williams, McClay, & Manal [27].

2.3 Statistical analysis

All values are expressed as mean ± standard deviation (SD) and statistical analyses of data were performed using IBM SPSS 21 (IBM Corporation, Armok, USA). Data were screened for normality of distribution and homogeneity of variances using a Shapiro-Wilk normality test and a Levene's test respectively. A one-way analysis of covariance (ANCOVA) was employed to compare differences in bone density ultrasonographic variables between competitive event-related groups (20-km men *vs.* 50-km men *vs.* 20-km women) and control groups adjusting for age. Pearson's correlation coefficient and regression analysis were performed to assess the relationships between calcaneus bone density related ultrasonographic variables and biomechanical factors in the race walking group only. Effect sizes (ES) were calculated for differences according to [28] and interpreted as small (>0.2 and <0.6). moderate (≥0.6 and <1.2). large (≥1.2 and <2) and very large (≥2 and <4) [29]. Significance was set at $p<0.05$.

3. RESULTS

The descriptive characteristics of the race walkers and control group are listed in Table 1. Participants are considered world-class as all possessed a personal best time faster than the entry standard required to participate in the Olympic Games of Rio de Janeiro 2016 (84.0 min for men and 94.0 min for women for 20-km). Fifty-km race walkers performed higher weekly training volumes than 20-km male and female race walkers ($p<0.001$; ES=1.6, large effect &

ES=2.4 very large effect, respectively). There were no significant anthropometrical differences between 50- and 20-km male race walkers, however female race walkers were shorter (p=0.001; ES=2.0, very large effect), lighter (p=0.003; ES=2.1, very large effect) and had greater sum of skinfolds (p=0.001; ES=4.5, very large effect) than the male race walkers. The control group were younger (p=0.001; ES=1.25, large effect) and had higher sum of skinfolds (p=0.001; ES=1.25, large effect).

No differences in calcaneal ultrasonographic parameters were found between race walkers and controls regardless of adjusting for age. However, various differences were found between 50-km and 20-km men and 20-km women race walkers (Figure 1). The 20-km race walkers presented higher SOS (p=0.032; ES=1.3, large effect) and SI (p=0.041; ES=1.3, large effect) values than the 50-km male race walkers. In contrast, BUA values differed only between male and female 20-km race walkers (p=0.049; ES=1.1, moderate effect). Mean T- and Z-score were higher in the 20-km male race walkers than the 50-km male race walkers (p=0.007; ES=2.4 and p=0.003; ES=3.0, very large effect, respectively).

In the race walking cohort, a greater weekly training load was associated with BUA values (r=-0.466, p=0.022). As it is described on table 2, initial loading rate of ground reaction force variables was found to positively correlate with greater BUA values (r=0.442, p=0.049), whereas not with the peak vertical forces. Additionally, greater time spent in ground contact was associated with higher SOS, BUA and SI values (r=0.696, p=0.003; r=521, p=0.039; r=0.679, p=0.004 respectively). Specifically, longer propulsive sub-phase of ground contact was related to a higher SOS (r=0.561, p=0.004) and SI values (r=0.496, p=0.014). There were not found any other significant association between spatiotemporal values or kinematics with BMD.

4. DISCUSSION

The main goal of this study was to analyse and compare calcaneal stiffness, a marker of bone mineral density (BMD), in elite 20-km and 50-km male and 20-km female race walkers. It was hypothesized that, because of the specific gait pattern employed by race walkers and distance specific training, calcaneal stiffness may differ between these groups. Indeed, within the race walking group differences were found in various bone ultrasonographic parameters between sex and competitive distances, however, no differences were found between the race walkers and control group.

The first notable finding was that the 50-km male race walkers presented lower SOS, SI, T- and Z-score values but not BUA values when compared to the 20-km male race walkers. The lower SOS values suggest the 50-km male race walkers possess lower soft tissue and differing micro-architecture of cortical thickness/elasticity that comprises the bone [6]. This subsequently results in a lower SI, T- and Z-scores and these discrepancies maybe related to differences found in training volume and intensity between these athletes of different distance specialization. Interestingly, a correlation between weekly training load and BUA values of the entire race walking group was found, where a greater training load was associated with a lower BUA, a marker of BMD [26]. Previous studies have found that recreational marathon runners possess greater calcaneal stiffness than half-marathon and 10-km runners [6]. However, our current findings in race walker suggest that too high training volumes may expose one to lower bone quality, especially when comparing elite to recreational athletes. This and a previous study have described that elite race walkers' training regimens consist of very high training volumes at low and moderate intensities [23]. These demanding training regimes increase the risk of low energy availability [30], usually associated with endurance athletes [31]. Low energy availability alters the endocrine system [12], with negative consequences on BMD [32]. Thus, the observed lower SOS, SI, T- and Z-score values found in the 50-km race walkers, suggest lower bone quality that appears to be related to possible energy availability from high training volumes and subsequent disruption in bone turnover and consolidation which may increase injury risk.

Moreover, the 50-km race walkers exhibited below normal T- and Z-score values (-0.8 ± 1.3 & -0.8 ± 1.2, respectively). Indeed, five of the eight (62.5%) 50-km race walkers in this study presented values of T- and Z-scores below -1.0, classifying them as osteopenic according to the World Health Organization classification system [33]. By contrast, no male 20-km race walkers, three of the eight female 20-km race walkers and one participant in the control group presented T- and Z-scores below -1.0. Collectively this finding suggests that ultra-endurance athletes maybe at a higher risk of bone injury possibly because of large training volumes, inadequate nutrition and subsequent low energy availability [30].

The following finding was that the 20-km male race walkers exhibited higher BUA values than the 20-km female race walkers but not SOS. This finding suggests the male 20-km race walkers posses greater trabecular bone tissue [26]. However, the difference between sexes in BUA appears to not influence the overall calcaneal SI and as previously mentioned three of the eight female race walkers presented with calcaneal stiffness T- and Z-scores below -1.0. Thus, the values observed in this cohort of female race walkers appear to be variable and make it difficult to make definitive interpretations from this finding. Sex differences in bone density have been previously documented, where low BMD in females have been influenced due to body size, dietary intake that influence energy availability and hormonal factors [10]. Other factors that may also contribute to these differences such as training intensity and ground reaction forces may play an important role, although no differences were found between training volumes in these race walking groups.

Lastly, some biomechanical values were associated with higher ultrasonographic values when assessing the race walkers as a population. All of these biomechanical variables were related to ground contact time related events and rate of loading. Greater time spent in ground contact of the gait cycle was associated with calcaneal stiffness variables whereas, greater time spent in the propulsion phase of ground contact was only associated with SOS and SI. These findings indicate that increased time in ground contact and more specifically during the propulsion sub-phase of ground contact are associated with greater calcaneal bone stiffness. Bone mineral density stimulation and bone strength are induced by mechanical forces produced by muscular and impact forces in runners [5], as previously described in endurance runners [10].

Unlike in running, race walking implies higher contact times and subsequently vertical ground reaction force is more sustained when trying to walk at the same velocity as running. This possibly places a greater reliance on the lower limb muscle contraction than in running [34] and may influence the calcaneal stiffness values observed in the race walkers with longer contact times of the gait cycle. Furthermore, the correlations found between BMD and the propulsive sub-phase of ground contact, could be attributed to the force placed on the calcaneus from the gastrocnemius and soleus during toe-off propulsion phase of gait [35]. Moreover, the absence of knee flexion reduces ground reaction force attenuation through movement and increases muscles demand in facilitating it [36].

Also associated with higher BUA values was a greater initial loading rate. It appears that the greater the loading rate the greater the marker of bone mineral density in race walkers. This may be an indication of bone adaptation to higher loads experience by some race walkers. A further interpretation of this correlation may also suggest that greater vertical force development upon initial ground contact, could indicate higher exercise intensity or mechanical stimuli [22,37]. This could contribute to the greater BMD values found in the 20-km male race walkers, who perform higher velocity and subsequent intensive training regimens than 50-km male and 20-km female race walkers [38].

Lastly, we acknowledge that although ultrasonography measurement is a valid method to determine BMD, bone mineral density assessment might be more specific with the use of dual-energy x-ray absorptiometry or quantitative computed tomography to provide a comprehensive overview of bone density and body composition in race walkers. Therefore, the outcome measures related to gait characteristics were only spatiotemporal in nature, and it may be that other biomechanical factors not reported here may be important determinants of bone density, in addition to muscular activation in the gastrocnemius and the tibialis anterior. Similarly, future research studying the relationships between bone density and biomechanical, nutritional and hormonal factors are thus warranted.

5. CONCLUSIONS

In this study, race walkers exhibited differences in the ultrasonographic values at the calcaneus bone compared between sex and competitive specialization, resulting in lower BMD values for 50-km male race walkers, with superior values for 20-km male race walkers. These differences may be explained by the specificity of the training loads for the 50-km race walkers, resulting a negative relation between weekly training volume to BMD factors. Additionally, initial loading and greater contact time and propulsive energy production by the musculoskeletal system could make positive changes in BMD values in elite race walkers. Thus, it can be suggested that race walkers who endure very high training volumes are required to optimize their training load and energy availability to ensure healthy BMD values.

Competing interests. Authors declare no conflict of interest. Additionally, authors declare that the results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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FIGURES LEGEND

Figure 1. Ultrasonographic characteristics of elite race walkers according to sex and competitive event. SOS, speed of sound; BUA, broadband ultrasound attenuation; SI, calcaneus stiffness index.

Table 1. Physical and physiological characteristics of elite racewalkers and the control group.

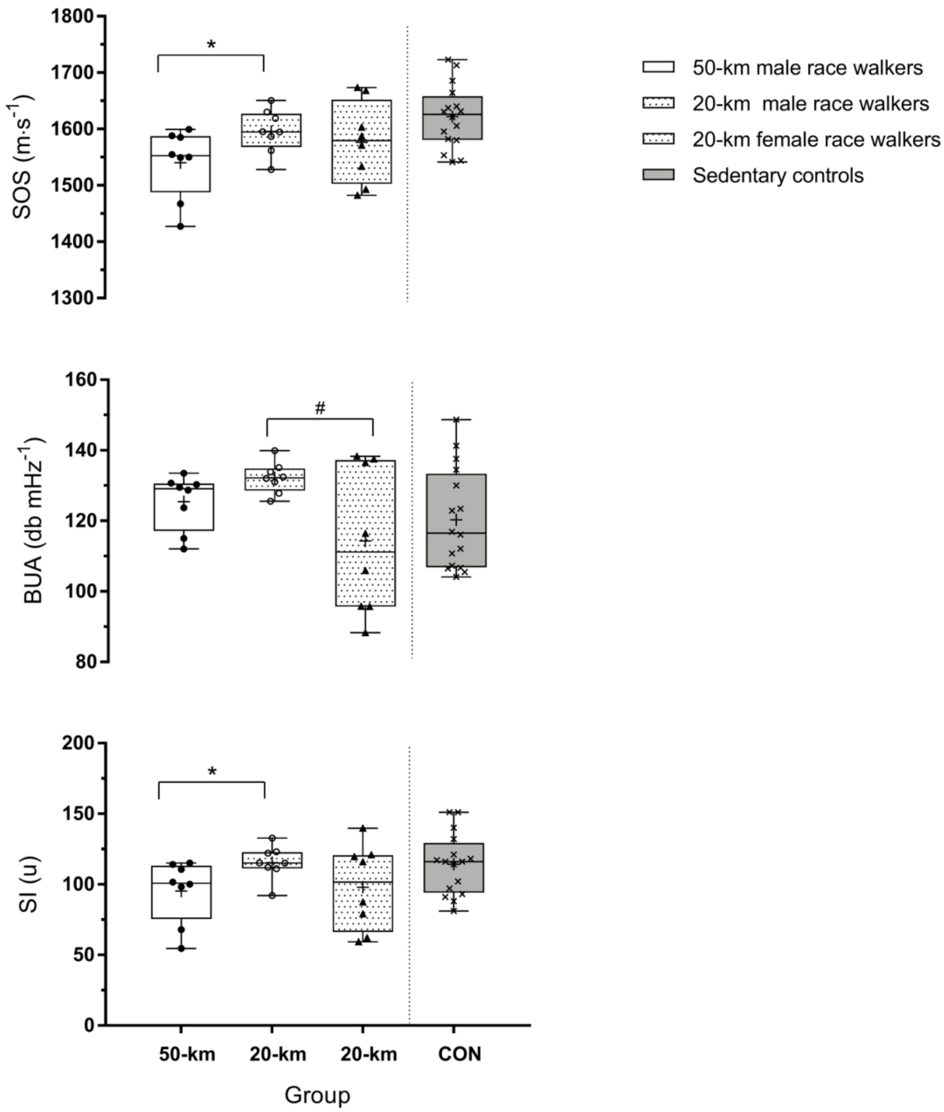
	50 km men (*n*=8)	**20 km men** (*n*=8)	**20 km women** (*n*=8)	**Control group** (*n*=16)
Age (years)	27.4 ± 6.4	23.8 ± 3.1	22.5 ± 2.8	20.0 ± 0.2
Body height (m)	1.77 ± 0.06*	1.77 ± 0.08*	1.65 ± 0.04	1.73 ± 0.09
Body mass (kg)	64.4 ± 6.1*	67.4 ± 6.2*	53.6 ± 3.7	65.8 ± 11.5
∑ 8 skinfold (mm)	45.9 ± 4.1*	46.1 ± 3.9*	71.9 ± 6.9	99.2 ± 23.3
20-km PB (min)	81.9 ± 1.8*	79.8 ± 1.9*	90.9 ± 2.8	-
Weekly Training (km)	197.5 ± 11.4*†	158.5 ± 16.5	146.8 ± 10.6	-

n, number of participants; PB, personal best; ∑ 8 skinfolds: biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh and medial calf. Values are presented as mean ± SD. *Significantly different from 20-km women ($p < 0.05$), #Significantly different from race walkers ($p < 0.05$), † Significantly different from 20-km men and women ($p < 0.05$).

Table 2. Relationships between ultrasonographic variables and various biomechanical and training load variables.

	SOS ($m \cdot s^{-1}$)		**BUA** ($db\ mHz^{-1}$)		**SI** (u)	
	r	***p***	***r***	***p***	***r***	***p***
Training load (km/week)		**NS**	-0.466	**0.022**		**NS**
Initial loading rate (BW/s)		**NS**	0.442	**0.049**		**NS**
Peak GRF (BW)		**NS**		**NS**		**NS**
Ground contact (%)	0.696	**0.003**	0.521	**0.039**	0.679	**0.004**
Braking sub-phase (%)		**NS**		**NS**		**NS**
Propulsion sub-phase (%)	0.561	**0.004**		**NS**	0.496	**0.014**

SOS, speed of sound; BUA, broadband ultrasound attenuation; SI, calcaneus stiffness index.
r, Pearson correlation coefficient; NS, no significant differences.



Ultrasonographic characteristics of elite race walkers according to sex and competitive event. SOS, speed of sound; BUA, broadband ultrasound attenuation; SI, calcaneus stiffness index.

169x202mm (300 x 300 DPI)

Addendum 4

Racewalking gait and its influence on racewalking economy in World-Class racewalkers.

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Race walking gait and its influence on race walking economy in world-class race walkers

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ABSTRACT

Aim: The aim of this study was to determine the relationships between biomechanical parameters of the gait cycle and race walking economy in world-class Olympic race walkers.

Methods: Twenty-One world-class race walkers possessing the Olympic qualifying standard participated in this study. Participants completed an incremental race walking test starting at 10 km·h^{-1}, where race walking economy (ml·kg^{-1}·km^{-1}) and spatiotemporal gait variables were analysed at different speeds.

Results: 20-km race walking performance was related to race walking economy, being the fastest race walkers those displaying reduced oxygen cost at a given speed (R = 0.760, $p < 0.001$). Longer ground contact times, shorter flight times, longer midstance sub-phase and shorter propulsive sub-phase during stance were related to a better race walking economy (moderate effect, $p < 0.05$).

Conclusion: According to the results of this study, the fastest race walkers were more economi cal than the lesser performers. Similarly, shorter flight times are associated with a more efficient race walking economy. Coaches and race walkers should avoid modifying their race walking style by increasing flight times, as it may not only impair economy, but also lead to disqualification.

ARTICLE HISTORY
Accepted 1 March 2018

KEYWORDS
Walking; sports performance; ground contact; footstep analysis; exercise physiology

Introduction

Race walking is a unique athletic event contested at the Olympic Games and other major athletic championships where race walkers typically participate over 20 km and 50 km. Success in this kind of endurance event has traditionally been associated with a number of physiological attributes, including a 1) high cardiac output; 2) high capacity to uptake and delivery oxygen to active muscles; 3) high lactate threshold; and 4) a low oxygen cost of transport (Nummela, Keränen, & Mikkelsson, 2007; Santos-Concejero et al., 2013, 2015).

Oxygen cost of transport has been found to most appropriately discriminate between performances in well-trained homogenous groups of athletes (Foster & Lucia, 2007). In fact, several studies have identified this variable as a critical factor contributing to performance in endurance sports including running (Santos-Concejero et al., 2015), cycling (Faria, Parker, & Faria, 2005), swimming (Toussaint, Knops, De Groot, & Hollander, 1990) or cross-country skiing (Sandbakk & Holmberg, 2013). The question arises whether the oxygen cost (also known as race walking economy and defined as the steady-state oxygen uptake at a given submaximal speed), would also influence race walking performance, especially in an elite population.

Inter-individual oxygen cost variations have been attributed to metabolic and physiological factors (Barnes & Kilding, 2015), neuromuscular factors (Barnes, Mcguigan, & Kilding, 2014), anthropometric factors (Bergh, Sjodin, Forsberg, & Svedenhag, 1991) and more importantly, to biomechanical variables (Padulo et al., 2013). Unlike other endurance sports, race walking is governed by strict biomechanical rules, as athletes are not allowed to have any visible loss of contact with the ground and must maintain a straightened knee from the initial contact with the ground until the vertical upright position (IAAF, 2015). The result of this is a distinct gait pattern and the need of not only endurance capacity, but also a great technical ability to perform at elite level (Hanley, Bissas, & Drake, 2013; Padulo et al., 2013).

For example, non-peer reviewed evidence suggests that when race walking, the optimum foot position at initial contact is directly under the centre of mass, as a foot ahead approaching zero would result in considerably reduced braking forces and, therefore, help maintain forward momentum (Summers, 1991). This would lead to a subsequent reduction in step length, which contrasts with research suggesting that larger step lengths would contribute to faster race walking speeds in elite race walkers (Hoga, Ae, Enomoto, & Fujii, 2003; Padulo, 2015). Other researchers have reported smaller vertical oscillations and longer flight times as key factors for increased walking speeds (Hanley & Bissas, 2017). Despite all previous research on the influence of biomechanical factors in race walking performance and economy (Morgan & Martin, 1986), the relationship between biomechanical gait variables and

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race walking economy in world-class race walkers are yet to be explored.

Thus, the aim of this study was to analyse whether spatiotemporal characteristics of the gait cycle, including ground contact and flight times, step length, cadence and the distribution of the different sub-phases during stance (initial contact, midstance and propulsion) are related to race walking economy in world-class Olympic race walkers.

Methods

Participants

Twenty-one world-class Olympic male race walkers from Spain, Sweden, Ireland, Australia and Canada agreed to participate in this study. All race walkers possessed the Olympic Entry Standard for Rio de Janeiro 2016 (1:24:00 in 20 km and 4:06:00 in 50 km for men) and the sample included current 20 km world champion and other World and Olympic medallists. Participants were tested during training camps in Spain, whilst they were in Europe for target IAAF Permit Race Walking meetings (i.e. Gran Premio Cantones de A Coruña). The race walkers were informed about all tests and possible risks involved and provided written informed consent before testing. The Ethics Committee for Research on Human subjects of the University of the Basque Country granted permission for this study (CEISH 66/2015).

Twenty-four hours before testing, race walkers were required to abstain from a hard training session and competition to be well rested. They were also requested to maintain their pre-competition diets throughout the test procedures and to abstain from caffeine and alcohol intake the day before testing. All testing sessions were performed under similar environmental conditions (20–23 ºC and at 09:00–13:00).

Design and protocols

Anthropometry

Anthropometrical characteristics were measured at rest by an accredited anthropometrist following the standardised techniques adopted by the *International Society for the Advancement of Kinanthropometry (ISAK)*. Height and body mass were measured in running shorts to the nearest 0.1 cm and 0.1 kg using a portable stadiometer (Seca, Hamburg, Germany) and digital scale (Tanita Corporation, Tokyo, Japan), respectively. Eight body skinfolds (triceps, subscapular, biceps, iliac crest, supraspinale, abdominal, front thigh and medial calf) were measured to the nearest 0.2 cm using a Harpenden skinfold caliper (British Indicators Ltd, St Albans, UK). Bone breadths and segmental girths were measured by a small bone sliding caliper (Rosscraft Innovations Inc, Vancouver, Canada) and a retractable measuring tape (Cooper Industries, Sparks, US), respectively.

Treadmill incremental test

All race walkers completed an incremental test on a treadmill (3p pulsar, H/P/cosmos, Germany) set at a 1% gradient (Jones & Doust, 1996). The treadmill was calibrated using a measuring wheel (ERGelek, Vitoria-Gasteiz, Spain) with a measurement error <0.5 m per 100 m interval. The test started at 10 km·h^{-1} without previous warm up and the speed was increased by 1 km·h^{-1} every 3 min until volitional exhaustion, with 30 s of recovery between stages (Bär, 1990). The analysed speeds were selected based on intensities corresponding to typical warm-up pace (10 km h^{-1}), long-walk training pace (12 km·h^{-1}) and Tempo training pace (14 km·h^{-1}).

During the test, heart rate was recorded every 5 seconds continuously by a heart rate monitor (Polar RS800, Kempele, Finland) and respiratory variables were continuously measured using a gas analyser system (Ergostik, Geratherm, Germany) calibrated before each session (Beijst, 2011). Volume calibration was performed at different flow rates with a 3 L calibration syringe (Ergostik, Geratherm, Germany) allowing an error ≤2%, and gas calibration was performed automatically by the system using both ambient and reference gases (CO_2 4.10%; O_2 15.92%) (Linde Gas, Germany).

In consideration of the slow component in oxygen uptake (VO_2), a slow increase in VO_2 during a constant-work-rate exercise performed above the lactate threshold (Jones et al., 2011), VO_2 (ml·kg^{-1}·min^{-1}) values collected during the last 30 s of three different speeds under the lactate threshold for all race walkers were averaged and designated as steady-state race walking economy (ml·kg^{-1}·km^{-1}). This was performed to ensure steady-state VO_2 values and to avoid possible biomechanical differences as a consequence of differing race walking speeds.

Immediately, after each exercise stage, capillary blood samples from the earlobe were obtained and analysed with a portable lactate analyser (Lactate Pro2, Arkray, KDK Corporation, Kyoto, Japan) to determinate the lactate concentrations ([La$^-$]). The lactate threshold of each participant was determined using a third order polynomial regression equation calculated with the plasma [La$^-$] versus speed (Santos-Concejero et al., 2014b). The point on the polynomial regression curve that yielded the maximal distance to the straight line formed by the two end data points was identified as the lactate threshold (Cheng et al., 1992).

Biomechanics

The spatiotemporal assessment was conducted during the treadmill test using an optical measurement system (Optojump-next, Microgate, Bolzano, Italy). The values of the 2nd and 3rd min of the race walking stages corresponding to 10, 12 and 14 km·h^{-1} were averaged and used for data analysis.

Optojump-next system consists of two bars (size 100 × 3 × 4 cm), one containing the reception and control unit, the other embedding the transmission electronics. Each of these contains 32 light emitting diodes (LEDs), positioned 0.3 cm from ground level at 3.125 cm intervals. The LEDs on the transmitting bar communicate continuously (1 kHz) with those on the receiving bar and has been shown to accurately determine gait spatiotemporal variables (Alvarez, Sebastian, Pellitero, & Ferrer-Roca, 2017). Gait cycle characteristics determined were ground contact time, swing time, step length, cadence and the percentage of the stance phase at which the different sub-phases occurs (initial contact, midstance and propulsion) (Padulo, Chamari, & Ardigò, 2014). During stance, the subphases were defined as: the initial contact sub-phase corresponds to the time from *initial ground contact* to *foot flat*; the midstance sub-phase from *foot flat* to *initial take off* and the propulsive sub-phase from *initial take off* to *toe off*.

Statistical analysis

All values are expressed as mean ± standard deviation (SD) and statistical analyses of data were performed using IBM SPSS 21 (IBM Corporation, Armok, USA). Data were screened for normality of distribution and homogeneity of variances using a Shapiro-Wilk normality test and a Levene's test respectively. The magnitude of differences or effect sizes (ES) were calculated according to Cohen's *d* and interpreted as small (>0.2 and <0.6), moderate (≥0.6 and <1.2) and large (≥1.2 and <2) according to the scale proposed by (Hopkins, Marshall, Tterham, & Hanin, 2009). Pearson's product-moment correlations were used to assess the relationships between spatiotemporal variables of the gait cycle and race walking economy and interpreted as small (>0.1 and <0.3), moderate (≥0.3 and <0.5), large (≥0.5 and <0.7) and very large (≥0.7 and <0.9) (Hopkins et al., 2009). A linear regression was performed to analyse the relationships between race walking economy and performance and 95% confidence intervals were calculated. Linear regression assumptions were checked using residual versus fitted, normal QQ, and Cook's distance plots. Significance for all analyses was set at $p < 0.05$.

Results

Descriptive characteristics

The physiological variables and descriptive characteristics of the race walkers participating in this study are listed in Table 1. All athletes possessed a personal best time faster than the entry standard needed to participate in the Olympic Games of Rio de Janeiro 2016 (1:24:00 for men), confirming that all participants were world-class elite race walkers. The homogeneity of the group was confirmed by a coefficient of variation <10% for all anthropometrical (except the ∑ 8 skinfold), physiological and performance related variables, including their personal best 20-km race walking times.

Figure 1 illustrates the relationship between race walking performance according to their best 20-km race time and race walking economy. Race walking economy at 14 km·h^{-1} was positively correlated with performance (R = 0.760, $p < 0.001$; very large effect).

Figures 2 and 3 depict changes in spatiotemporal parameters of the gait cycle as walking speeds increase. At increasing race walking speeds, step length and walking cadence increased by 24.8% and 12.2%, respectively. Ground contact time decreased from 0.34 ± 0.01 s at 10 km·h^{-1} to 0.28 ± 0.01 s at 14 km·h^{-1}, whereas the flight time increased from a double support to a flight time of 0.026 ± 0.007 s at 14 km·h^{-1}. Similarly, increasing race walking speeds were accompanied by a reduction of the initial contact sub-phase and propulsive sub-phase times in 19.1 and 29.7%, respectively. On the other hand, midstance sub-phase time increased in 101.1%.

Correlations between spatiotemporal gait variables and race walking economy at different speeds are depicted in Table 2. Significant correlations between flight time (s) at 12 km·h^{-1} (moderate effect) and 14 km·h^{-1} (moderate effect) were observed. Similarly, the percentage of the gait cycle spent in the swing phase correlated positively with race walking economy at 12 km·h^{-1} (large effect) and at 14 km·h^{-1} (large effect), whereas ground contact time (s) at 12 km·h^{-1} and 14 km·h^{-1} was negatively associated with race walking economy (large effect and moderate effect). The percentage of the gait cycle spent in the stance phase also correlated significantly with race walking economy at both 12 and 14 km·h^{-1} (large effect). Lastly, the midstance sub-phase showed a significant correlation with race walking economy at 12 km·h^{-1} (moderate effect) and at 14 km·h^{-1} (moderate effect), whereas the propulsive sub-phase correlated only at 12 km·h^{-1} (moderate effect).

Discussion

This study investigated the influence of spatiotemporal gait characteristics of race walking economy in world-class race walkers with an average personal best of 80.42 ± 2.13 min for 20 km (~ 4 minutes faster than the Olympic qualifying standard) and an average race walking economy of 241.30 ± 14.94 ml·kg^{-1}·km^{-1}. The first finding of this study was that race walking performance (according to their best 20-km race time), was positively associated with race walking economy at race pace (Figure 1), which implies that the fastest race walkers were more economical than the lesser performers. This association is in agreement with previous research in other endurance sports like distance running (Santos-Concejero et al., 2015), cycling (Faria et al., 2005) or cross-country skiing (Sandbakk & Holmberg, 2013) and further highlights the importance of movement efficiency in elite sport.

Table 1. Physical and physiological characteristics of elite race walkers (n = 21).

	Mean ± SD	CV (%)
Age (years)	26.6 ± 5.5	20.8
VO_2 at 14 km·h^{-1} (mL·kg^{-1}·min^{-1})	56.3 ± 3.5	6.2
20-km PB (min)	80.4 ± 2.1	2.7
Race walking economy (mL·kg^{-1}·km^{-1})	241.3 ± 14.9	6.2
LT (km·h^{-1})	14.6 ± 0.5	3.4
Height (cm)	177.1 ± 7.1	4
Mass (kg)	66.4 ± 5.8	8.7
∑ 8 skinfold (mm)	49.3 ± 6.8	13.7

n, number of participants; CV, coefficient of variation; VO_2 at 14 km·h^{-1}, oxygen uptake at 14 km·h^{-1}; PB, personal best; LT, lactate threshold; ∑ 8 skinfolds: biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh, and medial calf. Values are means ± SD.

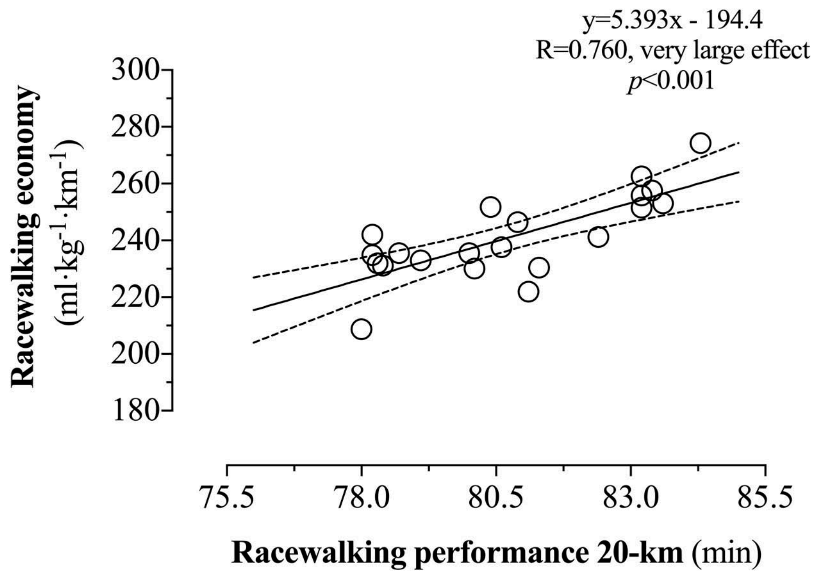

Figure 1. Relationship between race walking economy and participants' personal best performance in 20 km (n = 21). 95% confidence intervals are shown.

Previous research has hypothesised that certain biomechanical factors would be associated with greater movement efficiency in race walking, and that most economical race walkers may have distinct race walking patterns (Hanley & Bissas, 2017). In agreement with this hypothesis, we found significant relationships between race walking economy and ground contact characteristics (ground contact time, stance phase duration, midstance and propulsive sub-phases duration) as well as with flight time and swing phase duration (Table 2). Specifically, in race walking step length is restricted because race walkers have to elude visible flight times to elude disqualification (IAAF, 2015). It has been reported that race walking judges cannot observe a loss of contact below the threshold of 0.040 s (Lee, Mellifont, Burkett, & James, 2013), although the real limit may be a bit higher as the fastest rate a human eye can retain an image is 16 Hz, or 0.06 s (Winter, 2005). This implies that current rules of observation by the judges are flawed as race walkers are provided a "window" of non-perceptible flight times without the risk of disqualification. De Angelis and Menchinelli (1992) analysed the progression of flight times in international race walkers at different speeds, reporting values of 0.04 ± 0.007 s at

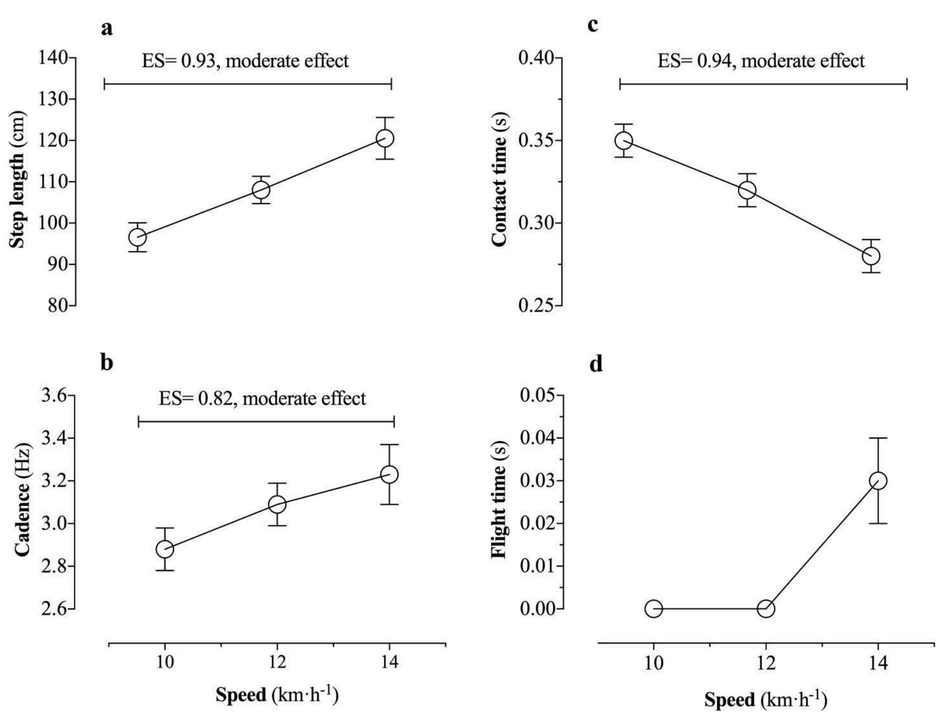

Figure 2. Step length (A), Step frequency (B), contact time (C) and flight time (D) at different speeds (n = 21). ES, effect sizes according to Cohen's d.

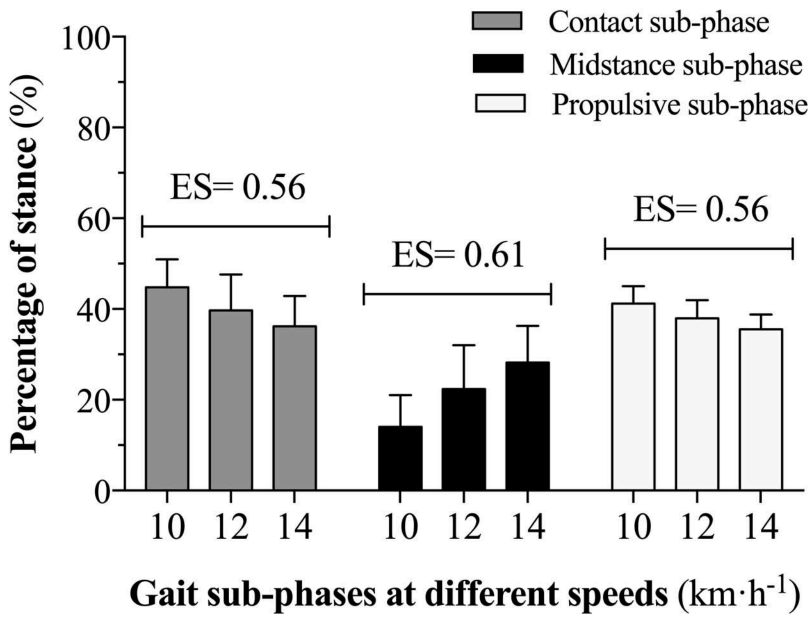

Figure 3. Percentage of time spent in each sub-phase of the stance phase (initial contact, midstance and propulsive) at different speeds (n = 21). ES, effect sizes according to Cohen's d.

14 km·h^{-1} (just in the limit of what is perceptible for the human eye). Similarly, Hanley, Bissas, and Drake (2011) observed flight times of 0.03 ± 0.01 s in competition. These results are in line with the values observed in this study (0.026 ± 0.007 s), suggesting that world-class race walkers can compete at fast speeds without a visible loss of contact with the ground (Figure 2). Interestingly, we observed positive correlations between flight time and race walking economy at 12 km·h^{-1} and at 14 km·h^{-1} (Table 2) and found that flight times increased when the speed was increased. Although we acknowledge that correlation does not always implies causation, this finding suggests that the most economical race walkers are those exhibiting shorter flight times at a given speed, resulting in a safer race walking technique in terms of risk of disqualification.

Previous studies on recreational and well-trained endurance runners (Paavolainen, Nummela, & Rusko, 1999; Santos-Concejero et al., 2014a) have reported that shorter ground contact times are strongly associated with lower oxygen cost at speeds ranging from 12 km·h^{-1} to 23 km·h^{-1}. Mechanistically, shorter ground contact times may reduce the duration of the braking phase during stance, which is usually associated with greater musculo-tendon stiffness and improved economy (Nummela et al., 2007; Paavolainen et al., 1999; Santos-Concejero et al., 2016). However, we found that longer ground contact times were related to a more efficient race walking economy at a given speed (Table 2). Due to the rules that govern the sport (i.e. a straightened knee from the first contact with the ground until the vertical upright position), race walkers may need a longer stance phase and longer contact times to apply force to ground and move forward without losing speed. As a result, to increase their walking speeds, race walkers would be required to maximise step length and step length:heigh ratio to an optimal value that does not increase the aerobic demands (Morgan & Martin, 1986), neither violate the rules of the sport. The step lengths observed in this study are in accordance with those reported by (Hanley et al., 2011) in an elite 20-km competition (68.0 ± 3.7% $vs.$ 68.1 ± 2.0% and 121 ± 0.7 cm $vs.$ 120.5 ± 5.1 cm, respectively). Once the optimum step length

Table 2. Interrelationships between biomechanical variables and race walking economy at different speeds (n = 21).

	10 km·h^{-1}		12 km·h^{-1}		14 km·h^{-1}	
Race walking economy	R	p	R	p	R	p
Step length (cm)	−0.327	0.147	−0.398	0.074	−0.116	0.618
Ration height:step length	−0.082	0.725	−0.193	0.403	0.051	0.826
Cadence (step/s)	0.333	0.140	0.397	0.075	0.123	0.594
Contact Time (s)	−0.253	0.268	**−0.524***	0.015	**−0.448***	0.042
Flight Time (s)	.a		**0.477***	0.029	**0.487***	0.025
Stance Phase (%)	.a		**−0.543***	0.011	**−0.607****	0.004
Swing Phase (%)	.a		**0.543***	0.011	**0.607****	0.004
Initial Contact sub-phase (%)	0.358	0.111	0.318	0.160	0.371	0.098
Midstance sub-phase (%)	−0.386	0.084	**−0.454***	0.039	**−0.460***	0.036
Propulsive sub-phase (%)	0.129	0.576	**0.470***	0.032	0.382	0.087

r, Pearson correlation coefficient; P, significance; NS, no significant differences. .a, Cannot be computed because at 10 km·h^{-1} Flight Time (s) is 0 (Constant), Stance phase (%) is 100% (Constant); and Swing phase (%) is 0 (Constant).

is achieved, any speed increase would be dependent on increasing cadence (Cairns, Burdette, Pisciotta, & Simon, 1986). In this study, race walkers increased their cadence from 2.88 ± 0.1 steps·s^{-1} at 10 km·h^{-1} to 3.23 ± 0.14 steps·s^{-1} at a typical race-pace of 14 km·h^{-1} (12.22% increase). However, neither step length nor cadence were correlated with race walking economy or performance in this study.

It was observed that when race walking speed increased, the time spent in the initial contact sub-phase decreased by 19.1% (from 44.8 ± 6.1% at 10 km·h^{-1} to 36.2 ± 6.67% at 14 km·h^{-1}). This reduction in the initial contact sub-phase has been attributed to an increase in hip extension velocity before contact (Lafortune, Cochrane, & Wright, 1989). During the midstance sub-phase, race walkers must produce the energy to overcome the braking forces generated in the previous sub-phase and to prepare the body for acceleration during the propulsion sub-phase (Levine, Richards, & Whittle, 2012). This may explain the correlation found between race walking economy and midstance sub-phase at both 12 km·h^{-1} and at 14 km·h^{-1} (Table 2). These findings agree with non peer-reviewed coaching opinion suggesting that the relation between gait sub-phases (initial contact, mid-stance and propulsive) may change the efficiency during race walking (Summers, 1991). Interestingly, although time spent in the propulsive sub-phase maybe beneficial in terms of race walking economy at slower speeds, it appears to be just a mechanical necessity as speed increases.

This is study was limited based on certain factors. These include a relatively small (n = 21) and very specific and homogeneous sample, which makes generalisation of the obtained results to all race walkers difficult. Similarly, race walking economy was assessed on a motorised treadmill. It is known that the lack of air resistance results in a lower oxygen cost compared with exercising outdoors at the same speed (Mooses, Tippi, Mooses, Durussel, & Mäestu, 2014). However, a 1% treadmill grade was chosen as previous research has reported that it accurately reflects the oxygen cost of exercising outdoors (Jones & Doust, 1996). In addition, spatiotemporal variables assessed in this study might vary from over-ground race walking when compared to treadmill race walking. Further, the outcome measures related to gait characteristics were only spatiotemporal in nature, and it may be that biomechanical factors related to stiffness and function of tendons, not reported here, are important determinants of race walking economy.

Future research studying neuromuscular activation in conjunction with ground reaction forces and 3-dimensional biomechanical analyses during over-ground race walking are thus warranted. These clinical, ecologically valid and in-depth measures may reveal additional answers for exceptional race walking performance in world-class race walkers and provide practical information for clinicians and coaches for ongoing management of elite race walking training programmes.

Conclusion

In summary, race walking performance was positively associated with race walking economy, which implies that the fastest race walkers were more economical than the lesser performers. Similarly, race walking economy was related to ground contact characteristics and swing time, which highlights the importance of race walking biomechanics for elite competitors in this sport. In this regard, shorter flight times (below of what is perceptible for the human eye) and longer ground contact times may reduce the oxygen cost of race walking in world-class race walkers. Since the rules of the sport penalise a visible lost of contact with the ground, coaches and race walkers should avoid modifying their race walking style by increasing flight times, as it may not only impair economy, but also lead to disqualification.

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Conflict of interest

Authors declare no conflict of interest. Authors declare that the results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Addendum 5

Biomechanical analysis of gait waveform data in elite race walkers and runners.

Manuscript Details

Manuscript number	GAIPOS_2018_1094
Title	Biomechanical analysis of gait waveform data in elite race walkers and runners
Article type	Full Length Article

Abstract

Research question. The aim of this study was to compare gait waveforms of world-class male race walkers and runners. Methods. Twenty-one elite race walkers and 15 elite runners performed overground gait trials at 12 km·h-1. Kinematic and ground reaction force data were collected, and joint kinetics calculated using inverse dynamics. One-dimensional statistical parametric mapping two-sample t-test assessed differences throughout the gait cycle on variables. Results. Race walkers exhibited longer contact and swing times, shorter strides and higher cadence ($P<0.001$). Race walkers had lower hip flexion-extension ($P=0.011$), greater knee extension ($P=0.001$) and reduced peak dorsi-plantarflexion during stance ($P=0.001$). Smaller ranges of frontal plane motion were observed in race walkers in both the knee and ankle ($P<0.01$), and greater hip adduction-abduction ($P=0.018$) and ankle rotation ($P=0.004$) were found in race walkers. Runners exhibited greater hip and knee flexion moments, and lower ankle flexion during 24-40% of the gait cycle. Discussion. Race walkers are required to modify their gait pattern to maintain a velocity similar to runners. Race walkers exhibited restricted ranges of motion in the knee and ankle sagittal planes, subsequently resulting in larger kinematic changes in the hip and increasing cadence and ground contact to maintain the same gait velocities. Thus, race walkers optimise their gait pattern from imposed gait contractions, resulting on a very specific and complex motor control task.

Keywords	Biomechanics; motion capture; race walk; running; high-performance
Taxonomy	Measurement Technique of Gait, Joint, Biomechanics of Gait

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Biomechanical analysis of gait waveform data in elite race walkers and runners

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ABSTRACT

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Methods. Twenty-one elite race walkers and 15 elite runners performed overground gait trials at 12 km·h^{-1}. Kinematic and ground reaction force data were collected, and joint kinetics calculated using inverse dynamics. · One-dimensional statistical parametric mapping two-sample *t*-test assessed differences throughout the gait cycle on variables.

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Discussion. Race walkers are required to modify their gait pattern to maintain a velocity similar to runners. Race walkers exhibited restricted ranges of motion in the knee and ankle sagittal planes, subsequently resulting in larger kinematic changes in the hip and increasing cadence and ground contact to maintain the same gait velocities. Thus, race walkers optimise their gait pattern from imposed gait contractions, resulting on a very specific and complex motor control task.

Key words: Biomechanics; motion capture; race walk; running; high-performance

INTRODUCTION

Endurance events in the Olympic Games and all major athletic championships include race walking and long-distance running. In both endurance disciplines, success by achieving the fastest mean speed, thus athletes require great physical capacity to accomplish this. However, unlike running, race walking is governed by a specific rule (Rule 230.2) [1] that enforces a unique gait pattern. Specifically, race walkers are restricted from exhibiting any visible loss of ground contact and are obliged to maintain a straightened knee from initial contact until the vertical upright position or risk warnings and disqualification.

Either running and race walking have been studied independently. As most studies have rather observed gait differences between training populations (recreational, national, elite) in race walkers or runners but not between disciplines [12,13]. Over the last decade, there has been an increase in race walking research, especially with complex considerations in motor variability [9] and functional data analysis of skilled and less-skilled individuals [7,8,10]. However, the full extent of gait waveform data of elite athletes have yet to been fully described, despite previous studies using two-dimensional videography [2–5] and three-dimensional motion capture [6–8]. However, to date, three-dimensional waveform comparisons between athletic disciplines have not been adequately conducted.

During running, the main propulsive mechanism of the runners is the flex-extension of the ankle and the knee during stance [2]. However, race walkers are restricted from the use of the knee mechanism due to the rules imposed. A comprehensive understanding of gait waveforms, whether kinetic or kinematic, during running and race walking in elite athletes provide insight into the specific and well-defined demands of these different gait disciplines. The use of one-dimensional statistical parametric mapping (1DSPM) provides the temporal assessment of gait data, that allows a broader understanding of the modifications required throughout the gait cycle that enable race walkers to maintain velocities similar to those of runners, [3]. Thus, the aim of this study was to analyse and compare the kinematics and kinetics of the gait cycle in world-class runners and race walkers using three-dimensional motion capture and force platform data. Additionally, these types of data analysis techniques can contribute to our better understanding of the gait sub phases [2].

METHODS

Participants

Twenty-one elite male race walkers (20 km: 80.8 ± 2.1 min) and 15 elite male endurance runners (21.1 km: 62.2 ± 1.0 min) agreed to participate in this study. All participants were informed about all tests and possible risks involved and provided written informed consent before testing. The Ethics Committee for Research on Human subjects of the University of the Basque Country (CEISH 66/2015) and the Research Ethics Committee of the University of Cape Town (HREC ref 151/2013) approved this study.

Design and protocol

Anthropometric characteristics of the participants, comprising height, mass and the sum of eight skinfolds (∑ 8 skinfolds: biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh and medial calf) were measured. The measurement of running and race walking economy was achieved by a constant running/race walking test (12 $km \cdot h^{-1}$) completed on a treadmill (3p pulsar, h/p/cosmos, Germany) [4]. The speed of 12 $km \cdot h^{-1}$

was chosen to allow the comparison between both running and race walking at a constant submaximal speed, avoiding any fatigue interference in the participants' gait patterns.

Participants completed race walking trials on a 30-m track in an indoor laboratory and were not provided with any technical instruction. During this time, three-dimensional marker trajectories were captured at 250 Hz, using a 10-camera Vicon Bonita motion capture system (Vicon, Oxford, UK). Synchronised collection of ground reaction force (GRF) data was sampled at 2000 Hz using a 900 × 600 mm force platform (AMTI, Watertown, MA, USA). Prior to testing, reflective markers were attached according to a modified Helen-Hayes Marker set [2]. The speed of the trials was set at 12 $km \cdot h^{-1}$ and accepted if the speed was within ± 4% of the target speed, when all markers were in view of the cameras and there was no visual evidence of athletes targeting the force platform.

Data analysis

For each trial, a complete gait of the participant`s right limb was analysed (ground contact-ground contact). Marker trajectory and force platform data were filtered using a low-pass fourth-order Butterworth filter with cut-off frequencies of 20 and 100 Hz respectively. Three-dimensional joint angles (ankle, knee and hip) were determined using the *PlugInGait* model and net resultant joint's sagittal moments using a Newton-Euler inverse dynamics approach [5]. Joint moments were expressed as external moments normalised to body mass ($Nm \cdot kg^{-1}$). Additionally, GRF data were normalised to bodyweight (BW) and the initial rate of loading was calculated [6]. Subsequently, joint kinematic and kinetic data are presented as waveforms that changed continuously throughout the entire gait cycle (101 data points), except for the vertical GRF waveform that is normalised to percentage of stance (101 data points).

Statistical analysis

Data were screened for normality of distribution using a Shapiro-Wilk's Normality test. Differences in descriptive characteristics, initial loading rate and ground contact time were assessed using independent *t*-tests or non-parametric Wilcoxon sign rank test, where appropriate. To detect differences between the kinematic and kinetic waveforms, 1DSPM was employed [3]. The running and race walking gait waveforms were compared using a one-way analysis of variance (SPM{f}). All 1DSPM analyses were implemented using the open-source 1DSPM code (v.M0.1, www.spm1d.org) in MATLAB (R2014a, 8.3.0.532, MathWorks Inc., Natick, MA, USA).

RESULTS

The athletic discipline specificity between groups resulted in large differences, as the race walkers were taller (P=0.009), heavier (P=0.004), greater ∑ 8 skinfolds (P=0.006) and higher oxygen cost of transport at 12 km·h^{-1} (P=0.001) (Table 1). Race walking and running speeds were similar between groups, however, differences in discrete kinetic and spatiotemporal variables were found (Table 1). To maintain a similar speed, race walkers exhibited longer ground contact times (P=0.001) and shorter swing times (P=0.001) than the runners. Additionally, race walkers also presented shorter strides (P=0.001) and higher cadences (P=0.001).

Large kinematic waveform differences were found between running and race walking at the same speed (Table 2 and Figure 1). Especially, in the sagittal plane, hip flexion-extension range of motion was more restricted in the race walkers than the runners between 0-81% of the gait cycle (F=7.935; P=0.011). In addition, greater knee extension was observed in the race walkers when compared with the runners throughout the gait cycle and an absent knee flexion peak during stance phase (F=8.142; P=0.001). Ankle dorsiflexion range of motion in the race walkers compared with runners was decreased with a later and smaller peak dorsi- and plantarflexion during stance at 0-47% of the gait cycle (F=8.271; P=0.001). In the frontal plane, decreased range of motion was found during stance in the race walkers in both the knee and ankle when compared with the runners at 20-48% and 0-46% of the gait cycle, respectively (F=8.142; P=0.008 and P=0.001, respectively). Greater ranges of motion in hip adduction-abduction were found in the race walkers than runners between 0-16% and 36-100% of the gait cycle (F=7.935; P=0.018 and P=0.004). Moreover, only the ankle exhibited differences in the transverse plane, where race walkers remained in greater ankle external rotation during stance (0-40%), early mid-swing (48-80%) and terminal swing (96-100% of the gait cycle) when compared with the runners (F=8.271; P=0.001, P=0.002 and P=0.001, respectively).

With regard to joint kinetic waveforms, runners exhibited greater hip flexion moments between 0-14% and 20-42% of the gait cycle when compared with the runners (Table 2). Runners presented with greater knee flexion moments at 1-5% and 7-38% of the gait cycle than the race walkers. Thereafter, knee flexion moments were greater in the race walkers over 28-38% of the gait cycle when compared with the runners. The ankle flexion moment was lower in the race walkers from 2-23%, and thereafter greater during 24-40% of the gait cycle when compared with the runners. Lastly, there was greater vertical GRF in the runners than the race walkers between 19-77% of the stance phase (Figure 2). Race walkers and runners showed similar GRF patterns during initial contact. However, the initial loading rate was higher in the runners (P=0.011) (Table 2).

DISCUSSION

The main goal of this study was to compare the joint kinematics and kinetics of the gait waveforms in world-class race walkers and runners. Both spatiotemporal variables and analysis of waveform variables presented insightful results. The main finding was that differences were found in all three joints and planes throughout the gait cycle. These differences are a consequence of the rules that race walkers are required to comply with (Rule 230.2) and are discussed in further detail below.

Spatiotemporal variables

Despite similar gait velocities, compared with runners, race walkers had higher ground contact times, in an attempt to avoid losing contact with the ground and to maintain a constant support leg on the ground. Whereas flight distances in elite race walkers have been previously observed to contribute to 13% of total step length, this factor has to be limited to avoid any visible loss of contact [7]. Thus, because flight times are restricted, stride length and cadence remain key factors in race walking performance [8]. Moreover, the distribution of sub-phases plays an important role in the effective displacement of the centre of mass [9,10]. This was noticeable during the late stance sub-phase, which lasted longer in race walking than running, increasing the propulsion time required to maintain a similar velocity.

Knee joint

The most distinct differences between running and race walking waveforms were observed in the sagittal plane of the hip, knee and ankle. In particular, reduced knee flexion was observed throughout stance in the race walkers when compared with the runners. Furthermore, the race walkers also exhibited knee hyperextension and delayed knee flexion during the propulsive phase of stance produced by the knee flexion-extension moment. An overall observation of the race walkers' knee flexion-extension gait cycle waveform illustrates a singular peak in knee flexion during the swing phase; notably, this is the absence of knee flexion during initial stance. The absence of this initial knee flexion peak in race walking has been suggested to be mechanically costlier than running at the same speed [11,12]. This phenomenon in running and normal walking during stance has been suggested to increase locomotion efficiency as a result of the energy-saving role of the Achilles tendon [13]. However, the flexion of the knee from the upright position to toe-off benefits the race walkers with a lower vertical oscillation of the body, consequently limiting flight time [7]. This study clearly distinguishes for the first time the magnitude of difference in knee flexion during stance in elite race walkers and runners simultaneously. Furthermore, there is reduced knee flexion throughout swing during race walking compared with running. This might benefit race walkers in facilitating knee extension during late swing and help to reduce flight time, but with the subsequent disadvantage of increased energy cost from an increased lower limb moment of inertia [14]

Hip Joint

The effect of having to achieve a straightened knee by initial contact and maintain it through mid-stance restricts the whole lower limb to one rigid lever. In response to this, the race walker adopts an exaggerated movement of the hip, which is one of the peculiar aspects of race walking [10,15]. Compared with runners, a reduced hip flexion at initial ground contact was observed in the race walkers to avoid exaggerated over-striding in preventing greater braking forces [8]. In addition, higher variability in the frontal plane was showed by race walkers to effectively increase step length. As the pelvis moves forwards (creating an abduction of the hip) in conjunction with the leg, it creates a forward momentum and longer step length with a decrease in stride width [16]. During the stance phase and in response to the need to straighten the knee, race walkers rotate the hip obliquely to avoid vertical displacement of the body's centre of mass [10,17]. While the hip continues to extend until the first part of the swing phase in runners, race walkers begin flexing the hip before toe-off; this prevents the leg from falling behind and drives the leg forwards into swing [7]. The larger hip abduction observed during swing appears to accommodate hip adduction during stance, as the stance leg is positioned below the body and the swing leg must move laterally outwards to pass it. The activation of the hip flexors and forward momentum created by pelvis rotation results in positive energy transfer, helping to the body to move over the straightened leg [18]. Subsequently, to ensure race walking gait is efficient and remains within the rules of competition, the hip has been suggested to be the predominant energy-generating joint in race walking gait [7].

Ankle Joint

In concordance with the other joints, ankle sagittal and frontal plane angles were limited in the race walkers when compared with the runners. To maintain a straight and stiff knee during initial contact, race walkers land with pronounced ankle dorsiflexion [8], which is exacerbated as a consequence of knee hyperextension. In this study, the runners exhibited a neutral ankle angle during stance at initial ground contact that progressed into greater dorsiflexion at mid-stance and greater plantarflexion at toe-off. This allows runners to store and transfer energy using the Achilles tendon but the ankle position during race walking does not allow this. In this study there is a pronounced ankle dorsiflexion at initial ground contact that progresses directly into a neutral – plantarflexion and then a delayed and suppressed dorsiflexion before a reduced plantarflexion toe-off [12]. The possible absence of the elastic forces in the calf and Achilles tendon obliges the race walkers to generate a greater plantarflexion moment during late stance than running [15]. Moreover, the reduced knee flexion that race walkers showed during the swing phase demands earlier and greater ankle dorsiflexion than in running. Whereas runners' ankle adduction and rotation are nearly neutral avoiding any wasting movement, race walkers have to ensure that the foot clears the ground and aids in a heel strike, requiring adduction of the ankle with an external rotation during swing phase [10,19,20].

Vertical ground reaction forces

As the restricted range of motion during race walking does not allow the body to store and transfer energy as effectively as during running, it is observed that the lower magnitude of the vertical GRF in the race walkers appears to be linked to the entire kinematic chain. A greater initial loading rate, in addition to greater vertical GRF observed during mid-stance, was observed in the runners. This might be perhaps because of the ability to store and transfer energy during ground contact more efficiently using the Achilles tendon and other energy transfer strategies based on a spring-mass model [13]. By contrast, race walkers exhibited lower GRFs during mid-stance. This reduced and delayed GRF peak might first be explained by avoidance of high GRFs due to the observed overall restricted range of motion of the lower limb joint angles during stance. In addition, this might be explained by the contrasting gait patterns used by both groups of elite athletes to propel against the ground. Whereas race walkers move the knee from a hyperextended position to a flexed one during late stance [7], runners use a flexion-extension pattern in the mid-stance phase. Thus, the technical restrictions oblige race walkers to transfer the energy using an extension-flexion pattern, causing the biggest differences in the joint flexion moments between both groups.

The last finding of this study was that the runners exhibited a better economy than the race walkers at the same sub-maximal speed. This was evident despite athletes being matched for athletic ability with regard to IAAF performance scores and both groups comprising endurance athletes who compete over similar distances. However, physical differences were also found between groups that might be relevant to the specific event that they participate in and also influence transport cost [21]. Interestingly, as running economy was expressed relative to body mass, the runners benefitted as a result of a reduced body mass (runners were 17% lighter than the race walkers); however, their smaller physiques might not be suited to race walking, where a greater stature is associated with longer step lengths [22], and where muscle activation is greater [12]. For both running and race walking, mechanical work and metabolic demand were suggested to be a principal factor affecting efficiency of locomotion [4,23]. Further research investigating the optimal biomechanics for efficient race walking economy is required to confirm this assumption.

Lastly, the use of the standard *PlugInGait* model was used to determine joint kinematics and kinetics. This model is acknowledged to provide highly variable transverse planes and limits our ability to effectively critique this plane [24]; the use of a different model might elucidate differences that this model cannot reveal for this study. However, the entire waveform data from this model remains relevant because it is useful for understanding the gait changes and further interpretation of the differences between elite runners' and race walkers' gait patterns. Further research investigating the supplementary assessments of joint powers and the assessment of electromyography might yield further insightful results.

CONCLUSIONS

Race walkers modify their gait pattern to maintain a velocity similar to runners whilst exhibiting restricted ranges of motion in the knee and ankle sagittal plane. Subsequently this resulted in larger kinematic changes in the hip and increased cadence and ground contact to maintain the same gait velocities. Thus, race walkers optimise their gait pattern from imposed gait contractions, resulting in a very specific and complex motor control task. Interestingly, these findings indicate that race walkers may require tailored technical, strength and conditioning training programmes specific to their athletic discipline race walking is evidently not running.

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CONFLICT OF INTEREST

Authors declare no conflict of interest. Authors declare that the results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

FIGURE LEGENDS

Figure 1. Kinematic data over an entire gait cycle. Mean ± SD for race walkers (constant line) and runners (dashed line). GREY bars denote periods where there were differences between-group.

Figure 2. Ground reaction forces data over the stance phase. Mean ± SD for race walkers (constant line) and runners (dashed line). GREY bars denote periods where there were differences between-group.

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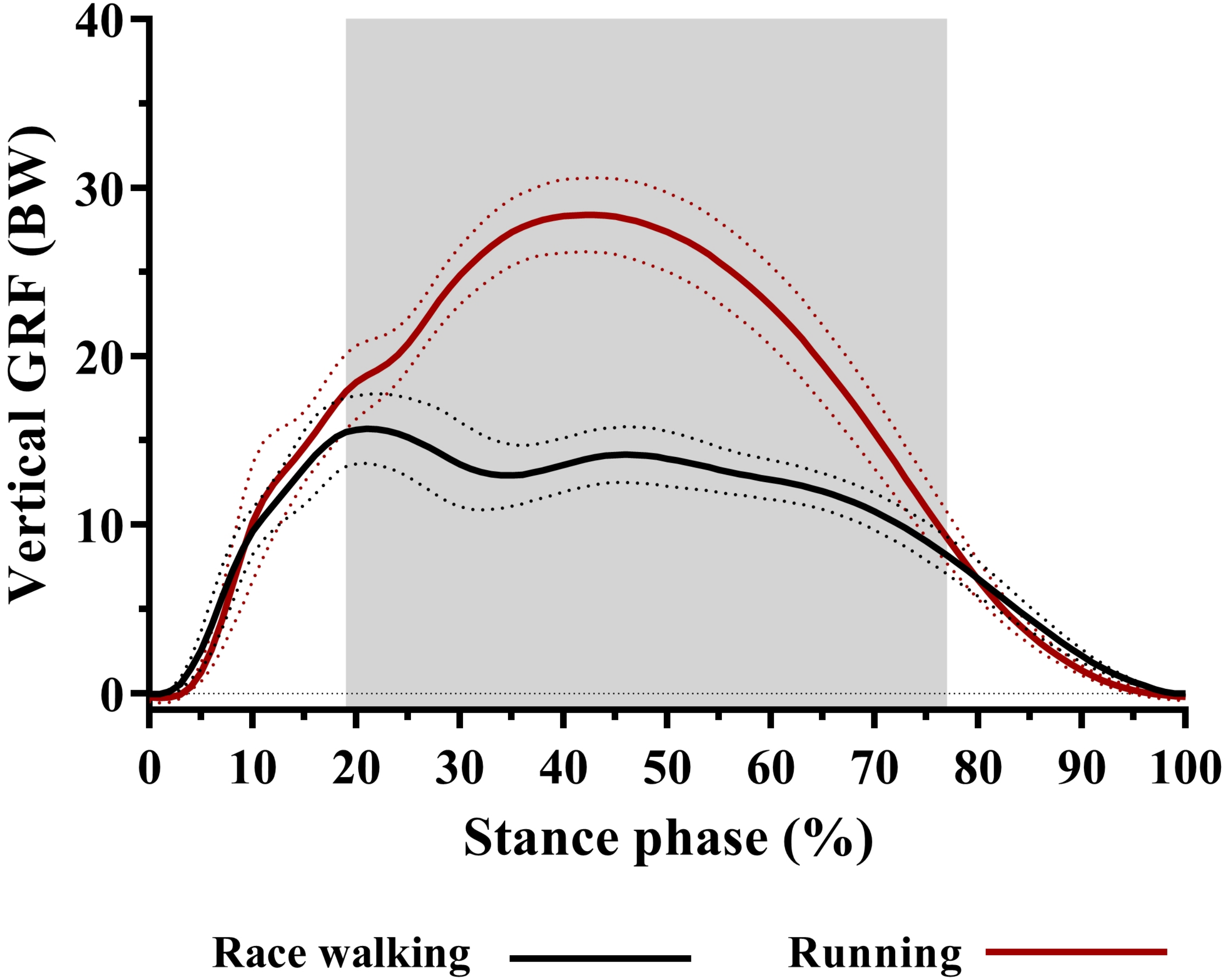
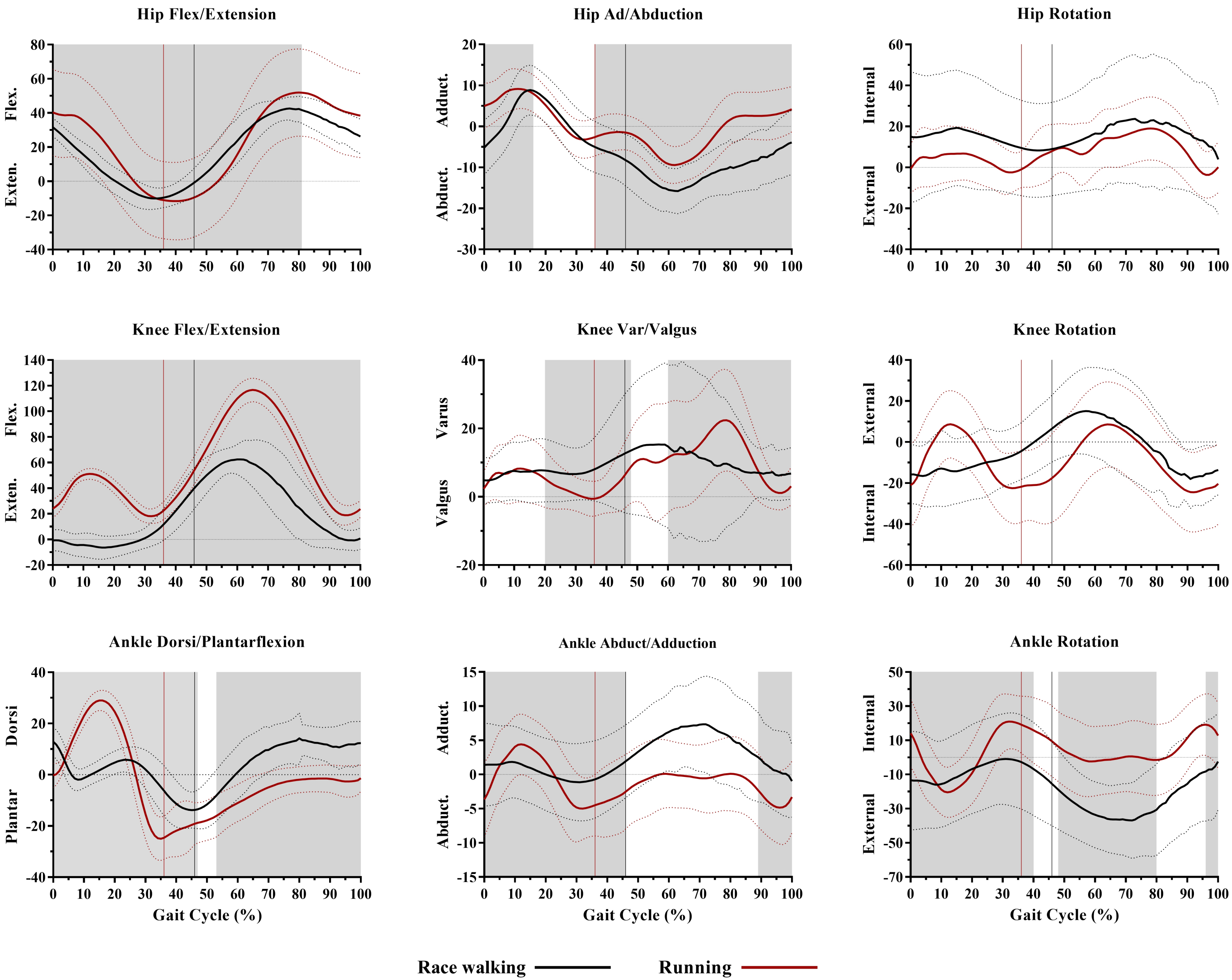


Vertical GRF (BW)
0
10
20
30
40
0
10
20
30
40
50
60
70
80
90
100
Stance phase (%)
Race walking
Running



Hip Flex/Extension
Flex.
Exten.
Hip Ad/Abduction
Adduct.
Abduct.
Hip Rotation
Internal
External
Knee Flex/Extension
Flex.
Exten.
Knee Var/Valgus
Varus
Valgus
Knee Rotation
External
Internal
Ankle Dorsi/Plantarflexion
Dorsi
Plantar
Ankle Abduct/Adduction
Adduct.
Abduct.
Ankle Rotation
Internal
External
Gait Cycle (%)
Race walking
Running

Table 1. Comparison of physical, physiological and gait characteristics (at 12 km· h^{-1}) of elite long-distance runners and race walkers.

	Race walkers (*n*=21)	**Runners** (*n*=15)
IAAF performance (u)	1184 ± 44 (20 km RW)	1100 ± 37 (21.097 km)
Age (years)	26.6 ± 5.5	23.7 ± 4.1
Height (m)	1.77 ± 0.07	1.71 ± 0.06**
Mass (kg)	66.4 ± 5.8	54.8 ± 6.0**
∑ 8 skinfold (mm)	49.3 ± 6.8	35.7 ± 8.6**
Economy at 12 km·h^{-1} (mL·kg^{-1}·km^{-1})	236.8 ± 16.2	192.6 ± 11.1**
Initial loading rate (BW·s^{-1})	27.67 ± 5.90	84.63 ± 36.92**
Ground contact time (s)	0.322 ± 0.011	0.237 ± 0.016**
Swing time (s)	0.304 ± 0.010	0.498 ± 0.044**
Step length (m)	1.08 ± 0.06	1.35 ± 0.10**
Cadence (step·s^{-1})	3.09 ± 0.10	2.47 ± 0.18**
Early stance (%)	0-16	0-13
Late stance (%)	17-46	14-36
Swing phase (%)	47-100	37-100

n: number of participants; ∑ 8 skinfolds: biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh and medial calf. Values are mean ± SD. Statistically significant difference *$p < 0.05$, ** $p < 0.01$.

Table 2. Summary table with respect to SPM analyses.

Variables	Critical threshold exceeded (% of gait cycle)	Supra-threshold p-values	Critical threshold (*f)
Kinematics			
Hip			
Sagittal plane	Stance and swing (0-81%)	P = 0.011	F = 7.935
Frontal plane	Early stance (0-16%)	P = 0.018	
	End stance and swing (36-100%)	P = 0.004	
Knee			
Sagittal plane	Entire cycle (0-100%)	P = 0.001	F = 8.142
Frontal plane	Mid stance and early swing (20-48%)	P = 0.008	
	Swing (60-100%)	P = 0.006	
Ankle			
Sagittal plane	Stance and early swing (0-47%)	P = 0.001	F = 8.271
	Swing (53-100%)	P = 0.013	
Frontal plane	Stance (0-46%)	P = 0.001	
	Late swing (89-100%)	P = 0.014	
Transverse plane	Stance (0-40%)	P = 0.001	
	Swing (48-80%)	P = 0.002	
	Late swing (96-100%)	P = 0.001	
Moments			
Hip			
Sagittal plane	Early stance (0-14%)	P = 0.001	F = 11.943
	Late stance (20-42%)	P = 0.002	
Knee			
Sagittal plane	Early stance (1-5%)	P = 0.001	F = 12.223
	Early and Mid stance (7-38%)	P = 0.001	
Ankle			
Sagittal plane	Early stance and early swing (2-40%)	P = 0.038	F = 12.182
Ground Reaction Force			
Vertical	Mid stance (19-77%)	P = 0.001	F = 8.998

Addendum 6

Muscle activation patterns correlate with race walking economy in elite race walkers: a waveform analysis.

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Muscle activation patterns correlate with race walking economy in elite race walkers: a waveform analysis

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ABSTRACT

Purpose: The aim of this study was to analyse the association between muscle activation patterns on oxygen cost of transport in elite race walkers over the entire gait waveform. **Methods**: Twenty-one Olympic race walkers performed overground walking trials at 14 $km \cdot h^{-1}$ where muscle activity of the gluteus maximus, adductor magnus, rectus femoris, biceps femoris, medial gastrocnemius and tibialis anterior were recorded. Race walking economy was determined by performing an incremental treadmill test ending at 14 $km \cdot h^{-1}$. **Results**: This study found that more economical race walkers exhibit greater gluteus maximus ($p=0.022$, $r=0.716$), biceps femoris ($p=0.011$, $r=0.801$) and medial gastrocnemius ($p=0.041$, $r=0.662$) activation prior to initial contact and weight acceptance. Additionally, during the propulsive and the early swing phase, race walkers with higher activation of the rectus femoris ($p=0.021$, $r=0.798$) exhibited better race walking economy. **Conclusions**: This study suggests that neuromuscular system is optimally co-ordinated through varying muscle activation to reduce metabolic demand of race walking. These findings highlight the importance of proximal posterior muscle activation during initial contact and hip flexor activation during early swing phase are associated with efficient energy transfer. Practically, race walking coaches may find this information useful in development of specific training strategies on technique.

Key words: oxygen cost of transport; efficiency; performance; electromyography; gait.

INTRODUCTION

Race walking possesses a unique locomotor strategy different from running because of the limitations arising from Rule 230.2 set by the International Association of Athletic Federations [1], which requires the athlete to present a straightened knee from initial contact to the "vertical upright position" and no visible loss of contact. Despite this restriction, athletes participating in this athletic discipline reach high speeds (e.g., 15 $km \cdot h^{-1}$) through biomechanical modification of their gait [2]. Nonetheless, race walking is more metabolically demanding than running at the same velocity as a result of the restrained biomechanics and neuromuscular coordination [3]. Previous research suggested that race walkers enhance movement efficiency using specific gait pattern strategies [4]. This was also confirmed by some researchers where shorter ground contact times, with shorter initial loading sub-phases, were associated with better oxygen cost of transport in elite race walkers [5].

Although recent gait analyses in race walking have mostly assessed peaks, range of motion and other discrete parameters of the entire gait cycle [5–7], a comprehensive understanding of the role and activity of the major muscles used throughout specific gait phases have not be conducted and could provide useful information. In addition, older electromyography studies assessed race walking before the implementation of modern race walking rules in 1995 [8] and more recent studies have analysed muscle moments, power and work through inverse dynamics [9–11]. These estimations established the role of particular muscle group contribution to the race walking movement, suggesting the importance of smaller deceleration phases during braking in early stance and subsequent smaller acceleration phases during late stance [12]. Assessing joint kinetics in elite men and women race walkers have provided novel insight of the role of specific lower limb muscles [9]. From a physiological perspective, assessing muscle activity may expand and improve the validity of modelled joint kinetic data, that may further reveal the role of neuromuscular factors on race walking locomotion. Previous measurements of muscle activity on race walking have been used to support kinematic findings [9], and determine muscle contributions race walking at different gradients [13]. However, the relationship between muscle activity and oxygen cost is required to fully understand the efficiency of the locomotion used in elite race walking.

In running, imbalanced antagonist:agonist co-activation ratios have been linked with an increased energy cost of transport [14], and previous research modelled lower limb muscle energy costs, using electromyography, were found to be higher in race walking than in running [15]. However, the key factor that might facilitate a more efficient oxygen cost of transport is the timing of muscle activation during the gait cycle [16], as pre-activation of lower limb posterior musculature has been found to relate to better running economy [17,18]. This implicates the lower limb musculature in ground reaction force attenuation during braking at initial ground contact, this is achieved through optimising joint stiffness for a more efficient transfer of energy [19]. Whether this neural preparation is also important in race walking has not been established, but is possibly crucial for athletes in this discipline given the high energy costs of race walking and restricted joint biomechanics compared with running [15].

Understanding the influence of muscle activation on oxygen cost of transport in race walkers is of interest as it provides insight into regulation of race walking kinematics that are associated with metabolic efficiency a marker of performance [5]. Additionally, this analysis may give new insights in coaching race walkers, with regard to the development of specific training strategies that consider the specific biomechanical and physiological demands of race walking. Thus, the aim of this study was to analyse the influence of muscle activation patterns on oxygen cost of transport in elite race walkers over the entire gait waveform.

METHODS

Participants

Twenty-one male Olympic race walkers agreed to participate in this study. All athletes possessed the 2016 Olympic Entry Standard for Rio de Janeiro (84 minutes for 20-km). All participants were informed about all tests and possible risks involved and provided written informed consent before testing. The Ethics Committee for Research on Human subjects of the University of the Basque Country (CEISH 66/2015) approved this study.

Design and protocol

Twenty-four hours before testing, the participants were required to abstain from a hard training session or competition to be well rested. They were also requested to maintain their pre-competition diets throughout the test procedures and to abstain from caffeine and alcohol intake the day before testing. All testing sessions were performed under similar environmental conditions (20 – 23ºC and between 09:00 – 13:00). Anthropometric characteristics of the participants, comprising height, mass and the sum of eight skinfolds (biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh and medial calf) were measured.

Participants completed race walking trials on a 30-m track in an indoor laboratory and were not provided with any technical instruction. During this time, synchronized collection of three-dimensional markers trajectories using a 10-camera Vicon Bonita 10 motion capture system (Vicon, Oxford, UK), ground reaction force data (AMTI, Watertown, MA, USA) and wireless surface electromyography (myON 320, Schwarzenberg, Switzerland) were recorded. The six muscles of interest for electromyography were gluteus maximus, adductor magnus, rectus femoris, biceps femoris, medial gastrocnemius and tibialis anterior. Before assessment, skin areas were prepared, and two surface electrodes placed according to established guidelines[20]. Leads and pre-amplifiers connected to the electrodes were secured with medical grade tape to avoid artefacts from lower limb movement during gait. The speed of the trials was set at 14 km·h^{-1} and trials were accepted if the speed was within ± 4% of the target speed, the entire right-foot made contact with a force platform and an entire gait cycle was visible from there on (ground contact-ground contact of the right foot). Motion capture and ground reaction force data were used only for gait event detection in this study.

Subsequently, race walking economy was determined by performing an incremental treadmill test (3p pulsar, h/p/cosmos, Germany). The slope was set at a 1% gradient [21] and the test started at 10 km·h^{-1}; after 3 min, the speed was increased by 1 km·h^{-1} every 3 min until 14 km·h^{-1} was completed, the velocity used for analysis. A 30 s recovery was taken between stages. During the test, oxygen uptake (VO_2) was continuously measured using a gas analyzer system (Ergostik, Geratherm, Germany). To ensure VO_2 steady-state measurements, the speed selected (14 km·h^{-1}) was slower than the individual lactate threshold of each athlete (further confirmed during the test by respiratory exchange ratios below 1.0 during the whole running bout for all athletes at each speed). VO_2 (mL·kg^{-1}·min^{-1}) values collected during the last 30 s of each stage were averaged and designated as steady-state race walking economy (mL·kg^{-1}·km^{-1}) to avoid the slow component in VO_2 [22].

Data analysis

The raw digital electromyography signal of sub-maximal trials were bandpass filtered between 30-450 Hz, then rectified and smoothed using root mean square (RMS) analysis at a 50 ms moving window [23]. Additionally, the EMG signals were normalised to each muscle activation peak. Subsequently, electromyography data were reduced to 101 points and presented as waveforms that changed continuously throughout the race walking gait cycle (a point per percentage of the gait cycle).

Statistical analysis

Data were screened for normality of distribution using a Shapiro-Wilk's Normality test. To detect relationships between muscle activity waveforms with race walking economy (at 14 km·h^{-1}), one-dimensional statistical parametric mapping (1DSPM) regression was employed [24]. The 1DSPM analyses were implemented using the open-source 1DSPM code (v.M0.4, www.spm1d.org) in Python (2.7, Python Foundation, USA). Significance for regressions were accepted at $p<0.05$.

RESULTS

The descriptive characteristics and physiological variables of the race walkers participating in the study are presented in Table 1. Specifically, this cohort presented a mean 20-km race performance of 80.49 ± 2.12 min and a race walking economy of 241.32 ± 14.91 mL·kg^{-1}·km^{-1}.

Posterior muscle activity and race walking economy

Relationships between posterior muscle activation and race walking economy were found in elite race walkers are listed in Table 2. During terminal swing (biceps femoris: 96-100% of the gait cycle, p=0.010, r=-0.801; gluteus maximus: 98-100%, p=0.022, r=-0.716) and initial weight acceptance (biceps femoris: 0-4%, p=0.011, r=-0.809; gluteus maximus: 0-6%, p=0.011, r=-0.723), higher activation of biceps femoris and gluteus maximus were associated with better race walking economy (Figure 1B and 1C). Additionally, a higher activation of the medial gastrocnemius during weight acceptance (5-8% of the gait cycle, p=0.041, r=-0.662) was found in more economical race walkers (Figure 1A). During the propulsion phase a greater medial gastrocnemius activation was also associated with a lower oxygen cost of transport (20-27% of the gait cycle, p=0.039, r=-0.668). Lastly, a lower activation of the biceps femoris was associated with more economical race walkers at 36-43% of the gait cycle (late propulsive phase to toe-off, p=0.012, r=0.697) (Figure 1B).

Anterior activity and race walking economy

During weight acceptance of ground contact, greater rectus femoris activation was associated with the most economical race walkers (8-11% of the gait cycle, p=0.016, r=-0.678). This coincided with a lower tibialis anterior activation at 6-12% of the gait cycle was associated with efficient race walking economy (p=0.033, r=0.671) (Figure 1D), whereas, during the propulsive phase (18-23% of the gait cycle) lower rectus femoris activation was associated better race walking economy (p=0.034, r=0.637) (Figure 1E). Subsequently, at the end of the propulsive phase (35-41% of the gait cycle), early- and mid-swing (42-53% and 63-68% of the gait cycle) greater rectus femoris activation was associated with lower oxygen cost of transport (p=0.018, r=-0.798; p=0.018, r=-0.798 and p=0.021, r=-0.813) (Figure 1E). Lastly, lower adductor magnus activation during early swing (43-50% of the gait cycle) was associated with better race walking economy (p=0.041, r=0.690) (Figure 1F).

DISCUSSION

The goal of this study was to explore muscle activation patterns over an entire gait cycle and its association with oxygen cost of race walking in elite race walkers. Interestingly, we have found some associations between oxygen cost of race walking and specific muscle group activation patterns at similar points of the gait cycle that may influence optimal race walking biomechanics.

Terminal swing and initial ground contact

Greater activation of gluteus maximus and biceps femoris at ground contact was associated with better race walking economy. Both posterior lower limb muscle relationships were found during late swing and continued into initial ground contact (96-100% and 0-6% of the gait cycle). This finding highlights the importance of proximal posterior muscle activation in contributing to oxygen cost of transport optimization, especially prior to and at initial ground contact. Previous research and our findings suggest these relationships activate in synchrony during this part of the gait cycle to prepare for ground contact and assist with joint stabilization and stiffness to lower oxygen cost of transport [16,19] . Thus, these observed phenomena appear to be related to the management of ground reaction forces at ground contact.

Large loading forces are experienced at initial ground contact, and the management of these forces is key to efficient energy transfer and reduced metabolic demand during ground contact [25]. Mechanisms to facilitate these forces appear to be associated with pre-activation [19] during terminal swing [16] and consequent joint biomechanics that enable efficient gait [18]. Thus, during initial ground contact, the biarticular muscle, biceps femoris appears to behave as a joint stabiliser for both the knee and hip, as similar findings have been found previously during running by Moore et al. [26] and Heise et al. [17]. While the gluteus maximus extends the hip.[9] The greater activation of gluteus maximus might reduce metabolic cost by optimizing neuromuscular control to assist efficient energy transfer (muscle tuning) [19] and joint movement (hip extension and stabilisation) [17]. Understanding these specific neuromuscular profiles in relation to race walking economy may assist coaches to consider the importance of training motor control pathways when working with their athletes[12]. By training these metabolic demands maybe be decreased by a reduction in co-activation through co-ordinate and selective activation profiles of antagonist-agonist muscles.

Midstance

Continuing from initial ground contact, associations between shank musculature and oxygen cost of race walking were found. Specifically, greater medial gastrocnemius and lower tibialis anterior activation were associated with favourable race walking economy. A similar finding has been previously observed in runners at 12 $km \cdot h^{-1}$ although this was over the entire ground contact phase [18]. This study further details the temporal nature of this relationship that was found between 5-8% of the gait cycle in the medial gastrocnemius and 6-12% of the gait cycle in the tibialis anterior. This overlap of associations illustrates the importance of the posterior chain and agonist-antagonist co-ordination during gait [14]. Considering a lower tibialis anterior activity was associated with better race walking economy and may be a feature of better technique as the activation of this muscle influence the stability of the ankle joint to optimally transition from initial ground contact to propulsion. Interestingly, higher activity has been suggested as a source of the shin pain frequently reported by race walkers [9,27] and thus excessive activation appears to be both uneconomical and possibly implicated with increased injury risk.

Further up the leg, greater rectus femoris activity was found to be favourable for metabolic cost before midstance (18-23% of the gait cycle). This finding, alongside previous other research could suggest that this biarticular muscle might act to mediate ground reaction forces through energy absorption through activation and simultaneous joint stabilisation of the knee and hip, allowing other structures of the lower limb to move in a way that improves energy transfer for locomotion [17,28].

However, during 35-41% of the gait cycle (post-midstance), lower rectus femoris activity was associated with better race walking economy. This is beneficial as increased activation of rectus femoris would possibly restrict gait kinematics, as this gait phase is associated with hip extension and knee flexion in order to shift the centre of mass.

Propulsion and swing

During terminal stance and early swing phases of race walking gait, a lower oxygen cost was associated with greater rectus femoris activation. [27] The exertion of the hip flexor torques that are generated by a higher activation of the rectus femoris at this time might benefit the race walkers with more efficient energy usage [10]. Due to the dynamic coupling of the body, the greater activation of the rectus femoris during late stance may be more effective as it could influence both the trunk and support leg segments [29]. This can be crucial given the contralateral stance leg's role functioning predominantly as a lever during midstance [9]. Additionally, this strategy could benefit race walkers via a better horizontal force production, and consequently a lower vertical oscillation of the body [28]. Thus, this finding suggests that the hip flexors play a substantial role in economical race walking by stabilizing and accelerating the lower limb through its bi-articular composition and proximal position.

Furthermore, the observation of a greater activation of the adductor magnus during early swing (43-50% of the gait cycle) is associated with higher race walking oxygen cost suggests that an excessive adduction of the hip is metabolically costly. Interestingly, this adduction of the hip is often observed in race walkers to increase step length and avoid visible loss of contact of the ground [30], but these findings suggest that this might be counterproductive from a metabolic perspective. Notably, during this phase the role of posterior muscle activation shifts, and greater biceps femoris activity was found to be possibly detrimental to race walking economy. This is important as greater activation of the antagonist biceps femoris during this period of gait might obstruct forward propulsion during toe-off as it is predominantly performed by the hip flexors [10].

Although the trials were performed on a treadmill and over ground, spatiotemporal data and walking velocity were found to be similar between conditions (Supplementary Table 1). Therefore, the comparisons can be made but one should not forget that differences between testing conditions do exist (surface, joint kinematics, belt vs. body speed etc.) but were minimized as much as possible. Further, understanding of the complex interaction between neuromuscular control and gait biomechanics could be further explored through analyses like functional data analysis or principal component analysis that could assist in collectively assessing features of such data on their impact on race walking economy.

PRACTICAL APPLICATIONS

This study provides unique insight into the complex role muscles perform throughout the race walking gait cycle and its correlations with performance. Interestingly, the associations found in this study between oxygen cost of race walking and muscle activation patterns emphasize the importance of optimal neuromuscular control in reducing the metabolic demand of movement. The ability to determine specific temporal relationships between race walking economy and muscle activation reveals possible facilitation of gait biomechanics that coaches and trainers may find useful to make athletes aware of. Thus, race walking coaches may find this study useful to incorporate technical advice and quotes for the race walkers oriented to the improvement of technically more efficient factors based on these neuromuscular activation insights.

CONCLUSIONS

This study illustrates that the most economical race walkers possess a refined neuromuscular system that is optimally co-ordinated to reduce the metabolic demand throughout race walking gait. It appears that this is achieved through the modulation of muscle activity to effect efficient joint biomechanics. Also, the importance of proximal posterior muscle activation at terminal swing and initial ground contact is noted in efficient energy transfer (ground reaction force facilitation) and consequent optimal joint biomechanics (hip extension and stabilisation). Lastly, the role of the hip flexors during the propulsive phase and the early swing phase was found to be associated with oxygen cost of race walking, that is suggested to assist in coordinating the acceleration of the lower limb.

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CONFLICT OF INTEREST

Authors declare no conflict of interest. Authors declare that the results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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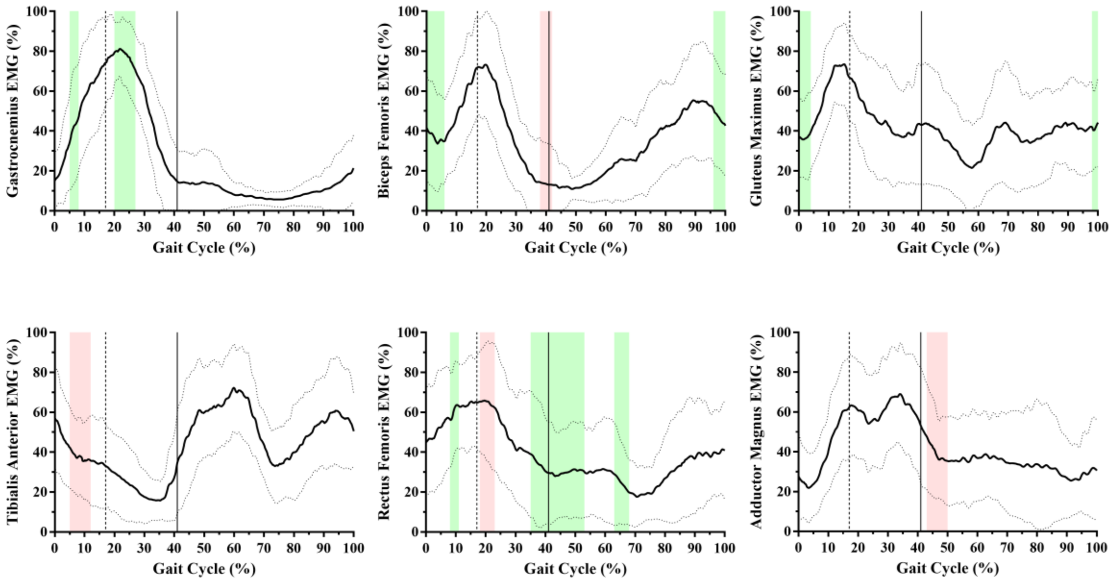

Figure 1: Muscle activation data over an entire gait cycle. Mean ± SD for each muscle. GREEN bands, negative correlation between muscle activation and oxygen uptake; RED bands, positive correlation between muscle activation and oxygen uptake.

Table 1: Physical and physiological characteristics of the race walkers (n=21).

	Mean ± SD
Age (years)	26.62 ± 5.53
Height (cm)	177.11 ± 7.13
Mass (kg)	66.41 ± 5.77
∑ 8 skinfold (mm)	49.33 ± 6.78
20-km race time (min)	80.49 ± 2.12
Race walking economy ($mL \cdot kg^{-1} \cdot km^{-1}$)*	241.32 ± 14.91

*: walking speed at 14 $km \cdot h^{-1}$; ∑ 8 skinfolds: biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh and medial calf.

Table 2: Summary table with respect to SPM analyses. Presented outcomes for regression of race walking race walking economy and muscle activity.

Muscles	**Critical threshold exceeded (% of gait cycle)***	**Supra-threshold p-values**	**r-values**
Gluteus Maximus	Weight acceptance (0-4%)	0.011	-0.723
	Swing (98-100%)	0.022	-0.716
Adductor Magnus	Swing phase (43-50%)	0.041	0.690
Biceps Femoris	Weight acceptance (0-6%)	0.011	-0.809
	Propulsive phase (38-43%)	0.012	0.697
	Swing (96-100%)	0.010	-0.801
Rectus Femoris	Weight acceptance (8-11%)	0.016	-0.678
	Weight acceptance (18-23%)	0.034	0.637
	Propulsive phase (35-41%)	0.018	-0.798
	Swing phase (42-53%)	0.018	-0.798
	Swing phase (63-68%)	0.021	-0.813
Gastrocnemius	Weight acceptance (5-8%)	0.041	-0.662
	Propulsive phase (20-27%)	0.039	-0.668
Tibialis Anterior	Weight acceptance (6-12%)	0.033	0.671

SPM, Statistical parametric mapping; *Critical threshold (*f) was calculated at F=3.96.

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Supplementary Table 1: Comparison of spatiotemporal values on a treadmill and over ground (using t-test).

	Treadmill	Over ground	p-values
Speed (km·h^{-1})	14.00 ± 0.00	14.03 ± 0.05	0.953
Ground contact time (s)	0.322 ± 0.011	0.328 ± 0.023	0.974
Swing time (s)	0.304 ± 0.010	0.299 ± 0.012	0.971
Step length (m)	1.08 ± 0.06	1.09 ± 0.09	0.974
Cadence (step·s^{-1})	3.09 ± 0.10	3.02 ± 0.14	0.978

Values are mean ± SD. Statistically significant difference *$p < 0.05$, ** $p < 0.01$.