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Section: Original Investigation

Article Title: 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·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·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 $km \cdot h^{-1}$ 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 [21] 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 analyzer 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 [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 $km \cdot h^{-1}$), 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 $mL \cdot kg^{-1} \cdot km^{-1}$.

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·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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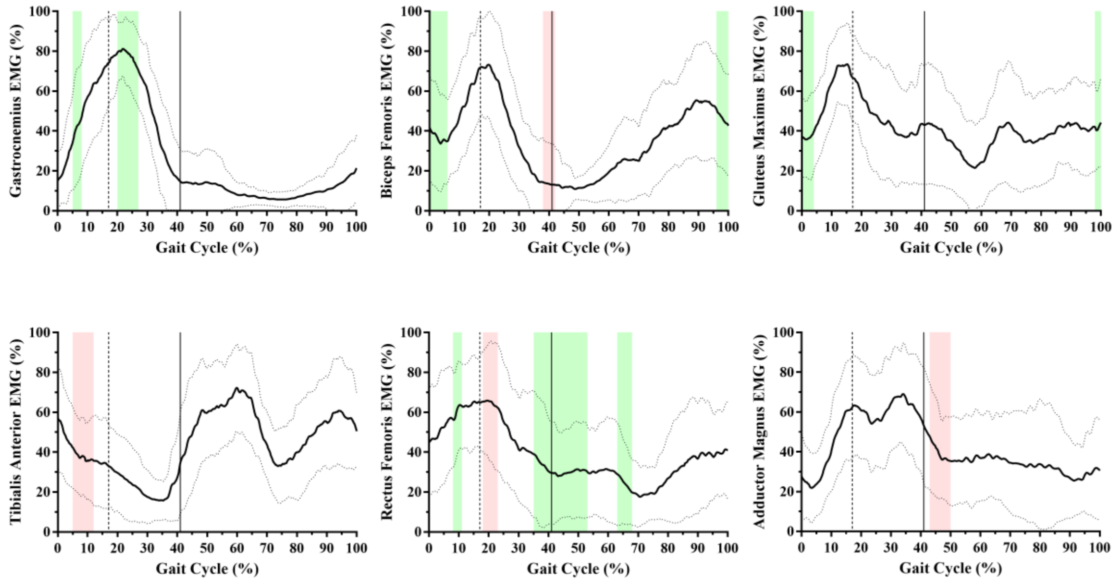

Figure 1: Muscle activation data over an entire gait cycle. Mean ± SD for each muscle. GREEN bands, negative correlation between muscle activation and oxygen uptake; RED bands, positive correlation between muscle activation and oxygen uptake.

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.

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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 ($km \cdot h^{-1}$)	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 ($step \cdot s^{-1}$)	3.09 ± 0.10	3.02 ± 0.14	0.978

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