Interlimb relation during the double support phase of gait: an electromyographic, mechanical and energy based analysis

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Abstract

Purpose: To analyse the interlimb relation and the influence of mechanical energy on metabolic energy expenditure during gait. *Methods:* 22 subjects were monitored as to electromyographic activity (EMG), ground reaction forces (GRF) and VO_2 consumption (metabolic power) during gait. *Results:* A moderate negative correlation was observed between the activity of tibialis anterior (TA), biceps femoris (BF) and vastus medialis (VM) of the trailing limb (TRAIL) during mid-stance to double support transition (MS-DS) and that of the leading limb (LEAD) during DS for the same muscles, and between these and gastrocnemius medialis (GM) and soleus (SOL) of the TRAIL during DS. TRAIL SOL during MS-DS was positively correlated to LEAD TA, VM and BF during DS. Also, the TRAIL centre of mass (CoM) mechanical work was strongly influenced by the LEADs, although only the mechanical power related to forward progression of both limbs was correlated to metabolic power. *Conclusion:* A consistent interlimb relation was observed in terms of EMG and CoM mechanical work, being the relations occurred in the plane of forward progression the more important to gait energy expenditure.

1. Introduction

Human gait is influenced by a multifactorial interaction that results from neural and mechanical organisation, including musculoskeletal dynamics, a central pattern generator and peripheral and supraspinal inputs [1]. In spite of the complexity involved, all control mechanisms must be considered and discussed based on the need of controlling the body center of mass (CoM) over the base of support [2].

Neuronal mechanisms, mediated at spinal level to achieve task-directed coupling of bilateral leg muscle activation, ensure the complex control of CoM movement [2]. In fact, experiments on interlimb coordination of leg muscle activation have confirmed that unilateral leg displacement during gait evokes a bilateral response pattern, with a similar onset in both sides [3, 4] but only when both limbs are performing a supportive role [5, 6]. This is consistent with the evidence that a large majority of midlumbar interneurones recipient from group II input are influenced by afferent fibres from both ipsilateral and contralateral sides [7] and by vestibulo- and reticulo-spinal pathways [8], and with the importance given to medium latency response from group II to feedback in the stance phase of gait [9].

The transition from one stance limb inverted pendulum to the next appears to be a major determinant of the mechanical work of walking [10, 11] and occurs mainly during double support (DS), as the two leg forces need to redirect the CoM velocity from a downward and forward direction to an upward and forward direction. It has been demonstrated that a low percentage of energy recovery in the DS [12] is related to the interruption of the energy-conserving motion of single support by an inelastic collision of the swing leg with the ground, leading to changes in velocities of the legs and the CoM [11]. This energy loss can be reduced by 75% through the application of a propulsion impulse in the trailing limb (TRAIL) immediately before collision of the leading limb (LEAD) [13, 14].

Simulations suggest that ankle plantar flexors and uni- and bi-articular hip extensors dominate the work output over the gait cycle [15]. These muscles, being active at late stance and at the beginning of stance, are therefore restoring energy to the body near DS [16]. A previous study demonstrated that the ground reaction force magnitude of the LEAD is associated with the electromyographic activity of the gastrocnemius medial (GM) during DS [17]; however, to the best of our knowledge, no prior study addressed the interdependence of the TRAIL and LEAD during DS in terms of muscle activity and CoM mechanical work. The understanding of this interlimb relation during walking is of interest to researchers involved in human movement science, but also to clinicians seeking to improve the walking ability of patients, particularity those presenting an asymmetric gait pattern, like post-stroke subjects.

The purpose of this study is to analyse the degree of interdependency of muscle activity and CoM mechanical work between TRAIL and LEAD during DS of walking and between the mechanical energy of each limb and the metabolic energy expenditure during gait.

2. Methods

2.1 Subjects

Twenty two adult subjects (10 males and 12 females) were recruited to participate in this study (age = 49.24±7.69 years, height = 1.66±0.09 m, body weight = 67.4±8.76 kg; mean±SD). The study excluded possible candidates presenting pain or with history of osteoarticular or musculotendon injury of the lower limb in the last 6 months, background or signs of neurological dysfunction or medication that could affect motor performance and history of lower limb surgery and lower limb anatomical deformities were excluded.

The study was approved by the local ethics committee and implemented according to the Declaration of Helsinki. All participants gave their written informed consent.

2.2 Instrumentation

The metabolic energy expenditure was measured by analysing inspired and expired air ($K4b^2$ model from COSMED, Italy). The values of vertical (F_z), anteroposterior (F_y) and mediolateral (F_x) components of ground reaction forces (GRF) were obtained from two force plates at a sampling rate of 1000 Hz (FP4060-10 and FP4060-08 models from Bertec Corporation, USA, connected to a Bertec AM 6300 amplifier and to a Biopac 16-bit analogical-digital converter, from BIOPAC Systems, Inc. USA). The bilateral electromyographic activity (EMG) of GM, Soleus (SOL), Tibialis Anterior (TA), Rectus Femoris (RF), Vastus Medialis (VM) and Biceps Femoris (BF) was monitored using surface EMG sensors (emgPLUX model from Plux Ltda, Portugal). The signals collected with a sampling frequency of 1000 Hz were pre-amplified at the electrode and then fed into a differential amplifier with an adjustable gain setting (25 - 500 Hz; common-mode rejection ratio (CMRR): 110 dB at 50 Hz, input impedance of 100 MΩ and gain of 1000). For the analog to digital signal conversion and bluetooth transmission to the computer, a wireless signal acquisition system (bioPLUX research, Plux Ltda) was used. Self-adhesive silver chloride EMG electrodes (Dahlausen 505) were used in a bipolar configuration and with a distance of 20 mm between detection surfaces (centre to centre). Skin impedance was measured with an Electrode Impedance Checker (Noraxon USA, Inc.). The EMG and force platform signals were digitised and stored for subsequent analysis in the Acqknowledge software (Biopac Systems, Inc., U.S.A). Gait timing was measured using a photovoltaic system (Brower Timing, IRD-T175, USA). All subjects used the same shoe type, in their adequate size.

2.3 Procedures

2.3.1 Skin preparation and electrode placement

The skin surface of the selected muscles' mid-belly and of the patella was prepared (shaved, dead skin cells and non-conductor elements were removed with alcohol and with an abrasive pad) to reduce the electrical resistance to less than 5000 Ω. The EMG electrodes were placed according to anatomical references (Table 1).

2.3.2 Data acquisition

a) Kinetic and electromyographic data

The EMG and GRF data were acquired while participants were walking using standard footwear over a 10 m walkway that included two separate force plates mounted in series near the midpoint of the walkway. Before the data acquisition, sufficient time was given so that participants became familiar with the experimental settings. They were allowed to walk over the walkway without explicit instructions, while we observed the starting point on the walkway where they placed one foot on the first force plate and the other on the second force plate according to their natural cadence. Considering that at the usual gait speed gait variability is minimised [18-20], the walking trials were carried out at a self-selected speed. The average values of 3 successful trials were used for analysis. A trial was considered successful when one foot had full contact with the first plate (TRAIL) and the contralateral limb had full contact with the second platform (LEAD).

b) Metabolic energy expenditure data

Subsequently, metabolic energy expenditure by each participant was measured while walking on a treadmill at the speed adopted during the walkway trials, since no differences in energy expenditure have been reported between these two conditions [21]. Before initiating the treadmill walking, the resting metabolism was measured during 3 minutes of quiet standing. A 3-5 minutes interval was set for subjects to reach a steady state during walking [22]. After this period, participants walked for 3 more minutes while oxygen uptake was measured [23]. Then, the standing values were subtracted from walking values. Halfway during each treadmill trial, the step frequency was registered and confirmed to be similar to the one obtained in the walkway test.

2.3.3 Data processing

a) Electromyographic activity

The EMG signals of the TRAIL and LEAD muscles during the transition between mid-stance and double support (MS-DS) and DS (Figure 1) were filtered using a zero-lag, second-order Butterworth filter with an effective band-pass of 20-450 Hz and the root mean square (RMS) was calculated. The EMG signals for each subject were normalised to the mean signal for each muscle over the entire gait cycle [24].

b) Kinetic parameters

The GRF data was low-pass filtered using a cutoff frequency of 8 Hz, with a fourth-order Butterworth filter by using a zero-lag and the CoM mechanical work was calculated for DS (Figure 1) according to the individual limbs method proposed by Donelan et al[10], 2002. In brief, the CoM accelerations in the three orthogonal directions were obtained from the sum of the GRF acting under each limb using the second law of Newton. Then, the CoM velocity was found by integrating acceleration over time. The integration constants were chosen under the following assumptions: the average vertical CoM velocity over a complete step is zero, average fore-aft velocity is equal to the average walking speed and medio-lateral CoM velocity at the beginning and end of the step is equal in magnitude but opposite in sign. A step was defined as the time between the beginning of one foot contact with the ground and the beginning of the opposite foot contact with the ground [10], which includes the first double support and single leg stance. The external mechanical work generated on the CoM by the TRAIL and LEAD individually was determined using the time integral of the dot product of the GRF of each limb and the velocity of the CoM and was normalized to the body mass of the subject (J/Kg). With this calculation of mechanical work, the net mechanical work was calculated for DS in both TRAIL and LEAD. To compare average mechanical work with the metabolic power, the mechanical work (J/Kg) was divided by the stride time (s), which was defined as the time between initial ground contact in the first force plate and a sudden large displacement of the centre of pressure on the second force plate, to obtain average mechanical power (W/Kg). For each participant, the data of 3 successful trials for each leg were averaged after analysis. Only CoM external work was calculated as it estimates satisfactorily the total CoM mechanical work performed, as during DS the angular displacements of the limbs relative to the CoM are relatively small, indicating that there is little internal work [10]. The EMG and mechanical CoM work and power data analysis was performed using Matlab software (MathWorks, USA).

c) Metabolic energy expenditure measurement

The metabolic energy consumption $\left(\dot{E}_{met}\right)$ was calculated from the VO_2 (ml/s) and respiratory exchange ratio (RER) values [23]:

$$\dot{E}_{met} = 4.94 \times RER \; + 16.04 \times VO_2.$$

To quantify the metabolic power (W/kg), the metabolic energy consumption $\left(\dot{E}_{met}\right)$ was divided by the body mass of the subject (kg).

Only the mechanical power and metabolic power were calculated as these variables have been demonstrated to be correlated [23, 25], and because the mechanical power has been described as the major time-varying variable that can be tracked from mechanical energy based analysis [26].

2.4 Statistics

The acquired data were analysed using the software Statistic Package Social Science (SPSS) from *IBM Company* (USA). Correlation between TRAIL and LEAD EMG activity was analysed using the Spearman's correlation coefficient and the correlation between CoM mechanical work of TRAIL and LEAD and between the metabolic and mechanical power was analysed using the Pearson's correlation coefficient. The Paired Samples T-test was used to compare the mechanical work and mechanical power between limbs. The statistical significance was set at $p<0.05$.

3. RESULTS

3.1 EMG during MS-DS and DS and CoM mechanical work during DS: interlimb relation

Values in Table 2 indicate that the higher the activity of TA, VM and BF during TRAIL MS-DS the lower the activity of the same muscles during LEAD DS. Also, TRAIL SOL activity during MS-DS was positively correlated to activity of TA, BF, VM and RF of the LEAD. The same muscles of the LEAD were the most correlated to the activity of the TRAIL during DS. Specifically, the higher the activity of TA, RF and VM of the LEAD, the lower the activity of SOL and GM of the TRAIL during DS, and the higher the LEAD BF, the lower the TRAIL SOL.

In line with the results obtained for the EMG, a strong dependency between TRAIL and LEAD during DS was also observed in terms of CoM mechanical work (Table 3). The findings suggest that the higher the absolute value of the negative LEAD

CoM mechanical work, the higher the absolute value of the positive TRAIL CoM mechanical work.

The TRAIL and LEAD CoM mechanical work was compared (Table 4) with the differences occurring only in the anteroposterior component, being higher in the TRAIL. Despite the interlimb relation observed as to EMG and CoM mechanical work, no statistical significant correlations were observed between EMG and CoM mechanical work.

3.2 Mechanical power during DS and metabolic power

The values obtained as to metabolic and mechanical power are shown in Table 4. The metabolic power was strongly related to positive mechanical power by the TRAIL ($r=0.731$, $p<0.001$) and negative mechanical power by the LEAD ($r=-0.723$, $p<0.001$) (Figure 2). As with CoM mechanical work, higher anteroposterior mechanical power was observed in the TRAIL in relation to the LEAD during DS, while no differences were observed in the other components (Table 4).

4. Discussion

This study aimed to assess the interlimb relation in terms of muscle activity and CoM mechanical work. Another purpose was to evaluate the influence of the mechanical energy of each limb over the metabolic cost of walking.

The results obtained as to the electromyographic activity reveal a consistent interlimb relation. It was interesting to note that the LEAD TA, VM and BF during DS depended, based on an inverse relation, on the activity of the same muscles of the TRAIL during MS-DS. The role of TA, hamstrings, gluteus maximus and quadriceps muscles of the LEAD has been stressed for the initial phase of stance [16]. From these, TA, hamstrings and quadriceps (specifically the vasti muscles) seem to be the most related to impact reduction during heel strike, having a non-determinant role in forward propulsion during MS-DS. The relation mentioned is therefore consistent to the evidence that the best proprioceptive information may come from un-modulated muscles [27]. Also, higher levels of TRAIL SOL activity during MS-DS were related to higher activity of the main responsible for LEAD impact reduction. Considering the agonist role of plantar flexors in forward propulsion [15, 22, 28], these finding suggest that the higher the TRAIL forward propulsion during MS-DS the lower the LEAD impact. However, considering that the EMG measurements alone could not provide information on the absolute contributions to the mechanical output of each muscle, or the relative contributions within a given condition, we suggest the combination of EMG with other analysis techniques, such as, computational modeling and simulation, to assess clearly the relation between TRAIL individual muscle function during MS-DS and LEAD impact during heel strike.

The results of this study also demonstrate that the lower the muscle activity related to impact reduction during heel strike (VM and TA), the higher the muscle activity related to forward propulsion during push-off (GM and SOL), corroborating models predicting that the TRAIL compensates for the energy loss provoked by the LEAD during heel strike through the action of plantar flexors [10, 13, 14]. This inverted relationship is consistent with the correlation observed in CoM mechanical work between limbs, as the higher the negative CoM mechanical work performed by the LEAD the higher the positive CoM mechanical work performed by the TRAIL. Assuming that gait kinematics remain similar between subjects at the velocity adopted in this study, then increases or decreases of muscle activity would be related to muscle mechanical output [29]. Considering the double inverted pendulum model, the activity of TA, VM and BF muscles would be associated to a reduction of the LEAD negative CoM mechanical work, and that of GM and SOL to an increase of the TRAIL positive

CoM mechanical work. However, our results failed in demonstrating an association between the activity of these muscles and CoM mechanical work. This can be due to the fact that the relationship between muscle activity and mechanical output depends on a number of nonlinear intrinsic properties, i.e., force-length-velocity relationships that make the relationship difficult to predict [29]. Given this limitation, it would be important to analyse the relation of joint moment power between limbs during DS and between the CoM mechanical work of each limb. Also, the kind of normalisation procedure used could be related to these results as, in spite of being useful in reducing inter-subject variability, it does not reflect the percentage of the maximum neural drive [30]. This may explain the correlation found in a previous study between GM activity of the TRAIL and the magnitude of GRF of the TRAIL [17]. As such, it would be important in future studies to analyse this relation using the maximum voluntary normalisation method.

The importance of the relation found between muscle activity of TRAIL and LEAD was reinforced by the strong influence of the anteroposterior component of negative (LEAD) and positive (TRAIL) mechanical power over the metabolic power of walking. Indeed, this finding is in line with the results presented by Gottscall[22], 2003, as to the influence of horizontal propulsive forces in metabolic cost of walking, and with results obtained in subjects with ankle impairment, as it was observed that both decreased TRAIL positive work [25] and increased LEAD negative work [23] were related to increased metabolic cost of walking.

5. Conclusion

The results of this study demonstrate that while the muscle activity of the TRAIL during MS-DS determined the muscle activity of the LEAD during DS, LEAD activity determined the activity of the TRAIL during DS. Also, the TRAIL CoM mechanical work was influenced by the LEADs, but only the mechanical power related to forward progression of both limbs was related to metabolic power.

The results obtained highlight the importance of plantar flexors' performance in gait economy, as they are the main responsible for forward propulsion, compensating the energy loss during the LEAD heel strike, but they also interfere with the level of activity of the LEAD muscles responsible for impact reduction during heel strike. Considering that low plantar flexor strength and power are common features in stroke subjects, future work will focus on quantifying muscle function and interlimb relation during DS of post-stroke gait.

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FIGURE CAPTIONS

Figure 1: Representation of the stance subphases defined according to the GRF curve. MS-DS of the TRAIL was defined as the time between the instant when the F_y of the TRAIL assumes the value zero till the instant when the F_z of the LEAD assumes a value equal to or higher than 7% of body weight; in this subphase, the EMG of TRAIL muscles was analysed. DS was defined as the time between the instant when the F_z of the LEAD assumes a value equal to or higher than 7% of body weight till the instant when the F_z of the TRAIL assumes a value equal to or lower than 7% of body weight.

Figure 2: Correlations found between mean metabolic power and AP mechanical power during DS (*significant correlation ($p<0.05$)).

TABLE CAPTIONS

Table 1: Anatomical references for electrode placement. Electrode locations were confirmed by palpation of the muscular belly with the subject in the test position, being the electrodes placed on the most prominent area.

Table 2: Correlation coefficient values and p-values obtained between the LEAD during DS and the TRAIL during MS-DS and DS.

Table 3: Correlation coefficient values and p-values obtained between the CoM mechanical work of the LEAD during DS and of the TRAIL during MS-DS and DS.

Table 4: Mean and standard deviation (SD) values of the CoM mechanical work and power during DS and metabolic power of gait ($*p<0.05$).

FIGURES

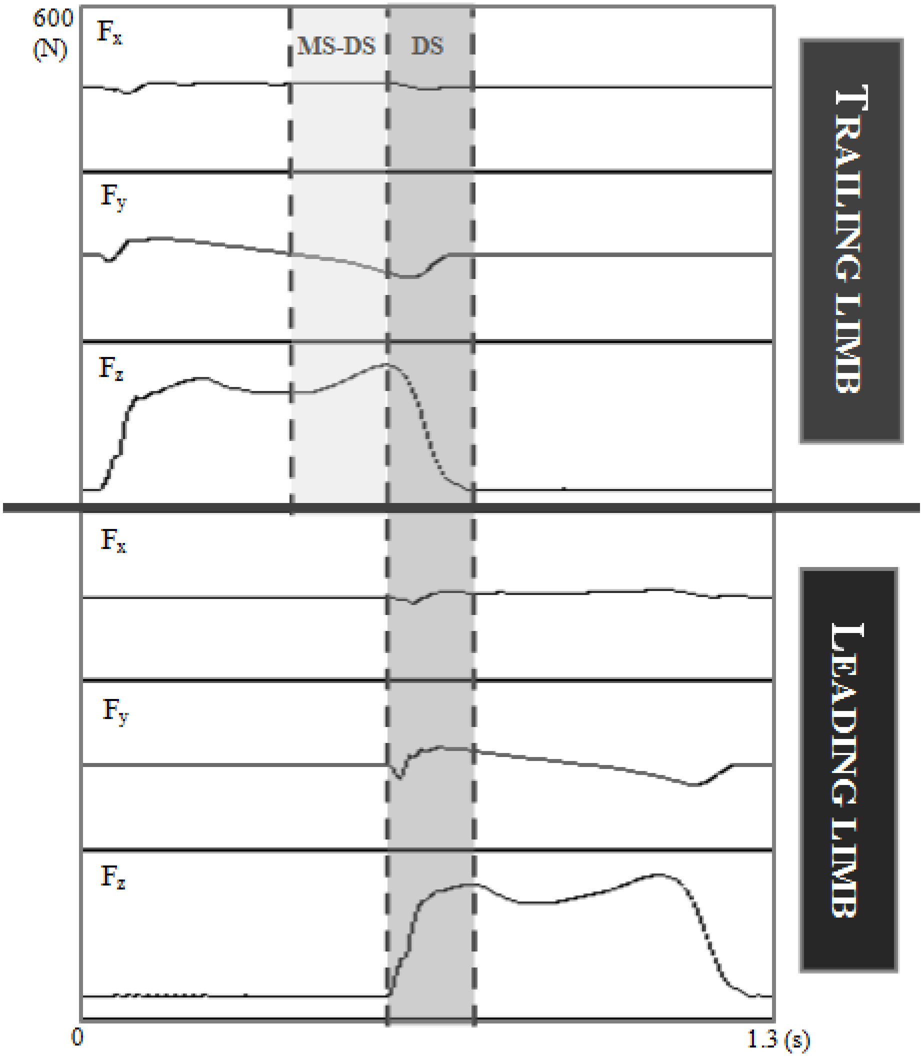

Figure 1

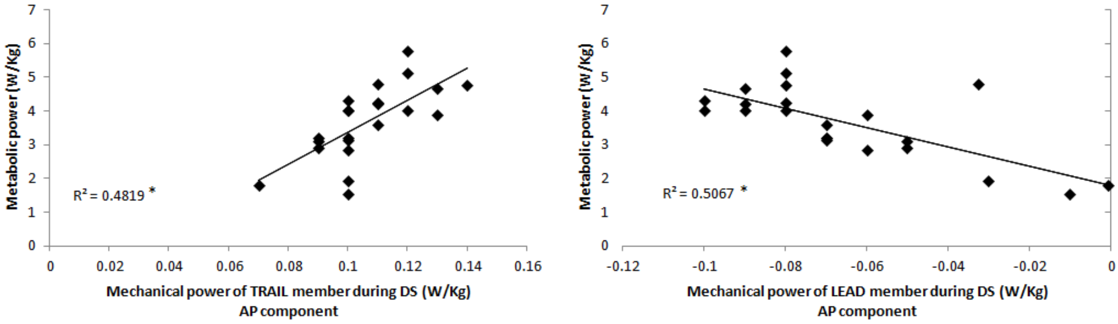

Figure 2

TABLES

Table 1

Muscle	**Electrode placement**
TA	1/3 on the line between the tip of the tibia and the tip of the medial malleolus
GM	Most prominent bulge of the muscle
SOL	2 cm distal to the lower border of the medial gastrocnemius muscle belly and 2 cm medial to the posterior midline of the leg
RF	1/2 on the line from the anterior spina iliaca to the superior border of the patella
VM	4 cm above the patella upper border and 3 cm measured medially and oriented 55º to a reference line drawn between the right antero-superior iliac spine and the patella centre
BF	1/2 on the line from the ischial tuberosity and the lateral epicondyle of the tibia
Ground electrode	Patella centre

Table 2

			LEAD during *DS*					
			GM	**SOL**	**TA**	**BF**	**RF**	**VM**
TRAIL	**GM**	*MS-DS*	ns	ns	ns	ns	ns	ns
		DS			r=-0.521 p=0.009		r=-0.452 p=0.027	r=-0.419 p=0.041
	SOL	*MS-DS*			r=0.603 p=0.001	r=0.511 p=0.011	r=0.507 p=0.011	r=0.455 p=0.026
		DS			r=-0.670 p<0.001	r=-0.554 p=0.005	r=-0.652 p=0.001	r=-0.668 p<0.0001
	TA	*MS-DS*			r=-0.577 p=0.003	r=-0.650 p=0.001	ns	r=-0.676 p<0.0001
		DS			ns	ns		ns
	BF	*MS-DS*			r=-0.425 p=0.038	r=-0.655 p=0.001		r=-0.639 p=0.001
		DS			ns	ns		ns
	RF	*MS-DS*						
		DS						
	VM	*MS-DS*			r=-0.423 p=0.039	r=-0.517 p=0.010		r=-0.581 p=0.003
		DS			ns	ns		ns

Table 3

		LEAD **CoM Mechanical work**			
		Mediolateral	*Anteroposterior*	*Vertical*	*Total*
TRAIL **CoM Mechanical work**	*Mediolateral*	ns	---	---	---
	Anteroposterior	---	r=-0.657 p<0.001	---	---
	Vertical	---	---	r=-0.890 p<0.001	---
	Total	---	---	---	r=-0.890 p<0.001

Table 4

Variable	**Component**	**Limb**	**Mean ± SD**	**p-value**
CoM Mechanical work ($J\ Kg^{-1}$)	*Mediolateral*	TRAIL	0.003 ± 0.001	0.076
		LEAD	-0.002 ± 0.0003	
	Anteroposterior	TRAIL	0.12 ± 0.005	<0.001*
		LEAD	-0.08 ± 0.007	
	Vertical	TRAIL	0.67 ± 0.057	0.265
		LEAD	-0.70 ± 0.063	
	Total	TRAIL	0.70 ± 0.054	0.954
		LEAD	-0.68 ± 0.041	
Mechanical power ($W\ Kg^{-1}$)	*Mediolateral*	TRAIL	0.003 ± 0.001	0.135
		LEAD	-0.002 ± 0.001	
	Anteroposterior	TRAIL	0.11 ± 0.005	<0.001*
		LEAD	-0.07 ± 0.006	
	Vertical	TRAIL	0.60 ± 0.04	0.057
		LEAD	-0.65 ± 0.06	
	Total	TRAIL	0.66 ± 0.06	<0.001*
		LEAD	-0.62 ± 0.04	
Metabolic power ($W\ Kg^{-1}$)	----	----	3.63 ± 0.25	----