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► **To cite this version:**

Anne-Marie Heugas, Isabelle Siegler. Combined hip angle variability and RPE could determine gait transition in elite race walkers. *Motor Control*, 2019, 23 (2), pp.216-229. 10.1123/mc.2017-0027 . hal-03528227

**HAL Id: hal-03528227**

**<https://hal.science/hal-03528227>**

Submitted on 17 Jan 2022

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**TITLE PAGE****Combined hip angle variability and RPE could determine gait transition in elite race  
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**Running head:** Elite race walkers' gait transition factors**Date of manuscript submission:** April 3, 2017**Corresponding author:** Anne-Marie Heugas

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**ABSTRACT.**

The aim of this study was to investigate the role of energy cost in locomotion, specifically the rate of perceived exertion (RPE) and movement variability in gait transition for eight race walkers (RW) and seven non-race walkers (NRW). We hypothesized that a group of correlated variables could serve as combined triggers. Participants performed a Preferred Transition Speed (PTS) test, exhibiting a higher PTS for RW ( $10.35 \pm 0.28 \text{ km}\cdot\text{h}^{-1}$ ) than for NRW ( $7.07 \pm 0.69 \text{ km}\cdot\text{h}^{-1}$ ), because RW engaged in race walking before switching to running. None of the variables increased before transition and dropped in PTS, which challenged the hypothesis of a unique transition variable in gait transitions. Principal component analysis showed that combined hip angle variability and RPE could determine gait transitions in elite RW and NRW. Thus, human gait transition may be triggered by a pool of determinant variables, rather than by a single factor.

**Keywords:** Race walking; Preferred transition speed; Energy cost; RPE; Movement variability.

Walking is the preferred terrestrial gait pattern used by humans at locomotion speeds not exceeding approximately  $7.2 \text{ km}\cdot\text{h}^{-1}$ . This is the speed at which humans usually switch to running and is referred to as the “preferred transition speed” (PTS) (Thorstensson & Roberthson, 1987). Gait selection that results from a metabolic energy minimization strategy has long been considered a major factor in gait transition (Raynor, Yi, Abernethy, & Jong, 2002). However this theory has been contested. Several existing studies have found a significantly lower PTS than the energetically optimal transition speed (EOTS), as well as no

effect of aerobic fitness and training level on PTS (Brisswalter & Mottet, 1996; Rotstein, Inbar, Berginsky, & Meckel, 2005). Some studies have argued that gait transition could result from a minimization of biomechanical constraints or discomfort and the potential risk of injury (Hreljac, Imamura, Escamilla, Edwards, & MacLeod, 2008; Pires, Lay, & Rubenson, 2014; Prilutsky & Gregor, 2001). According to dynamical systems theory, gait becomes unstable at some point when velocity is increased, that is in a state of equilibrium in which small disturbances will produce large changes. This instability leads to more variability and gait transition occurs in a bid to return to a more stable gait, associated with a reduction in energy costs (Turvey et al., 1999). Variability in kinematic measures is used as an indicator of coordinative changes as well as the stability of the coordination pattern. Using standard deviation (SD) to quantify variability, Dietrich and Warren (1995), and Brisswalter and Mottet (1996) identified greater variability in the discrete relative phases of hip-ankle and knee-ankle joint angles, and in stride duration prior to gait transition, respectively. In contrast, other studies did not find such an increase before transition (Kao, Ringenbach, & Martin, 2003) or between the coordinative patterns of intra- and inter-limb couplings (Seay, Haddad, van Emmerik, & Hamill, 2006).

Because of the large number of variables involved, the mechanisms by which individuals switch gait are not yet fully understood. Furthermore, most studies have mainly focused either on metabolic, movement variability or perceived exertion responses related with gait transition. Indeed, only a few have observed the relationship between the various variables (Beaupied, Multon, & Delamarche, 2003; Ranisavljev et al., 2014). None of the above-mentioned variables can be seen to singularly subtend the transition phenomena whilst still influencing them to some extent; thus, it could be hypothesized that humans rely on a combination of these variables when evaluating the need to shift gait. The main purpose of the present study was to gain an insight into the way in which the combination of metabolic,

movement variability and perceived exertion variables could yield a single or small number of combined variables to act as transition triggers. The composition of these combined variables could be dependent on the participants' characteristics and training status; for example, expertise in the field of walking or running.

Within this framework, an investigation of competitive race walkers is of particular interest, because they have learned to walk with a specific locomotive technique and at velocities that are much higher than PTS. The rules of race walking make it compulsory for race walkers to remain in contact with the ground and to keep the leg locked from “the first contact with the ground until the leg is in the vertical upright position” (International Association of Athletic Federations, 2013). Thus, race walkers are required to produce greater metabolic power and bring into play greater coordination control (Cavagna & Franzetti, 1981; Hoga, Ae, Enomoto, & Fujii, 2003; Pavei, Cazzola, La Torre, & Minetti, 2014). Previous studies have shown that race walkers are able to maintain their specific walking gait throughout a race, despite fatigue. This suggests that race walking performance is related more to biomechanical factors than physiological factors (Brisswalter, Fougeron, & Legros, 1998; Hoga et al., 2003). Thus, race walking can be seen as a relevant model system for studying gait transition. Only one study has sought to examine the PTS in race walkers, showing that race walkers who performed at a moderate level had a higher PTS and EOTS compared with physically fit individuals. There was also a trend to a smaller difference between PTS and energetically optimal transition speed (Ziv & Rotstein, 2009). The authors concluded that minimizing the energy cost of locomotion (EC) was not the main cause for gait change. They hypothesized that race walkers may be able to delay the sensation of localized muscle discomfort by reducing the stress in the plantar and dorsiflexors. Indeed, the choice of a preferred mode of locomotion with changing speed could be influenced by

perceived exertion (Hampson, St Clair Gibson, Lambert, & Noakes, 2001; Prilutsky & Gregor, 2001; Ziv & Rotstein, 2009).

The rationale of this experiment was to investigate the respective roles of EC, rate of perceived exertion (RPE) and movement variability in the triggering of gait transitions for a group of elite race walkers and a control group of physically fit individuals. We aimed to evaluate how these variables could combine to serve as transition triggers for both types of participants. Indeed, elite race walkers constitute a contrasting population for whom the interplay of the studied variables could be different to that of the control group. By comparing the two groups, we sought to identify the transition phenomena that are common to both groups and those that are group dependent. To this end, participants were asked to perform a PTS test. In addition, to examine how the individual variables evolve around gait transition, we also carried out a principal component analysis (PCA) to identify these combined variables in the two groups.

## **Methods**

### **Participants**

A total of 15 participants took part in this study and were divided in two groups. A race walking group (RW) included eight race walkers (one female and seven males) who competed at national and international levels. A non-race walking group (NRW) included seven students (three females and four males) who were enrolled at the Faculty of Sport Sciences. This research was approved by our Institutional Review Board (IRB) and informed consent was obtained from participants. The general physical characteristics of the participants are presented in Table 1.

TABLE 1. Anthropometric, physiological characteristics of the two groups (mean  $\pm$  SD) and performance characteristics of race walkers: race times on 20 km (hh:mm:ss) convert to mean race speed (km.h<sup>-1</sup>).

	Non-race walkers (n=7)	Race walkers (n=8)
Age (yr)	25 $\pm$ 3.9	29 $\pm$ 9.5
Height (cm)	168 $\pm$ 9.1	175 $\pm$ 5.5
Weight (kg)	61 $\pm$ 9.8	66 $\pm$ 9.7
Leg length (cm)	107 $\pm$ 4.6	93 $\pm$ 9.5
$\dot{V}O_{2\max}$ (mL. O <sub>2</sub> . kg <sup>-1</sup> .min <sup>-1</sup> )	58.3 $\pm$ 7.4	60.9 $\pm$ 6.7
VT (mL O <sub>2</sub> .kg <sup>-1</sup> .min <sup>-1</sup> )	44.9 $\pm$ 5.3	51.8 $\pm$ 8.7
20 km race time (hh : mm : ss)		01:33:13 $\pm$ 00:04:13
V-20km (Km.h <sup>-1</sup> -)		12.9 $\pm$ 0.6

### Experimental set-up

The experiment was performed on a Laufergotest treadmill with computer-controlled speed. The participants wore a portable breath-by-breath gas analyzer (Cosmed K4b<sup>2</sup>, Rome, Italy), which was calibrated prior to each test according to the manufacturer's instructions (Eisenmann, Brisko, Shadrick, & Welsh, 2003). Heart rate (HR) was measured during all the tests using a monitoring system (Polar, Kempele, Finland). Two foot switches (Biometrics System) were placed inside each shoe — under the phalanges in the medio-lateral direction and under the calcaneus in the anterior-posterior direction — to determine the occurrence of ground contact for each foot during walking and running. Electrogoniometers were attached to each participant's ankle and hip joints to measure joint angles and variability when walking and running. Knee angle was not measured because the race walking rules meant that

variability was not expected at knee level and, by the fact that ankle and hip are considered as the main determinant of propulsive torque and speed (Pavei et al., 2014). The analog signals from the foot switches and electrogoniometers were recorded at 100 Hz (DATAlink Model DLK800, Biometrics Ltd., UK).

## **Procedure**

Each participant completed two data collection sessions and was asked to rest for the 2 days preceding each session. Before each session, participants were given at least 15 min to familiarize themselves with walking and running on a treadmill. They adopted a comfortable speed using their preferred gait pattern followed by successive increases and decreases in treadmill speed in order to get used to such changes. All tests were performed under controlled environmental conditions (i.e., 20-23°C temperature and 40-65% relative humidity).

### *Session 1: $\dot{V}O_2max$ determination*

An incremental maximal running test (treadmill slope of 3%) was conducted to determine maximal aerobic power ( $\dot{V}O_2max$ ). The initial test velocity was set at 10 km.h<sup>-1</sup> for both groups, and increased by increments of 1 km.h<sup>-1</sup> every minute to the point of voluntary exhaustion. Fingertip capillary blood samples (Lactate Pro LT, Arkay Inc., Kyoto, Japan) were collected before the test, immediately after exhaustion, and after a three-minute recovery period.

### *Session 2: PTS determination*

After the warm-up, the participants performed an incremental protocol to determine the individual PTS (Diedrich & Warren, 1995; Raynor, Yi, Abernethy, & Jong, 2002). The

treadmill gradient was set at 0%. The participants performed two successive PTS test trials in a “walk-to-run” condition, where the treadmill speed was increased every minute by 0.5 km.h<sup>-1</sup> from a comfortable pace of 5 km.h<sup>-1</sup> or 6 km.h<sup>-1</sup> for the non-race walkers and race walkers groups, respectively. The participants were not informed of the speed. Between each trial, HR was monitored to insure that participants had enough recovery time (HR < 120 bpm) in order to avoid fatigue effect. During this test, the participants were instructed to adjust gait pattern to the speed in a natural way which felt most comfortable: “please walk or run, whichever feels most comfortable”. The participants shifted gait at a particular treadmill speed (PTS) and after the one-minute duration of this speed plateau was over, the treadmill speed was further increased to confirm the switch to a new mode of locomotion (PTS +1).

#### *Rate of perceived exertion (RPE)*

Prior to undertaking the first transition trial, the participants familiarized themselves with Borg’s 15-point scale of ratings of perceived exertion (Borg, 1986). They were then instructed to indicate their RPE score during each velocity plateau during the PTS test.

### **Data analysis**

#### *Preferred Transition Speed*

Gait transitions were determined using foot switches. The transition stride was identified as the first walk-to-run stride containing a flight phase (Diedrich & Warren, 1995). For each participant, PTS was computed as the mean of two treadmill speeds at which participants shifted gaits during the two walk-to-run test trials.

#### *$\dot{V}O_2max$*

The  $\dot{V}O_2max$  was defined as the highest  $\dot{V}O_2$  value ( $mlO_2.kg^{-1}.min^{-1}$ ) obtained in two successive 15-second intervals. The criteria used to determine  $\dot{V}O_2max$  were as follows: (a) an increase in running speed without a concomitant increase in, (b) a maximal heart rate within 10% of the age-predicted maximum heart rate, (c) blood lactate above  $8\text{ mmol.l}^{-1}$ , and (d) a respiratory exchange ratio over 1.1. (e.g. Howley, Bassett, & Welch, 1995).

#### *Metabolic energy*

In the PTS test, the oxygen consumption rate ( $\dot{V}O_2$ ,  $ml\ O_2.kg^{-1}.min^{-1}$ ) was continuously recorded and averaged over the final 30 seconds of each one-minute velocity period corresponding to a metabolic steady state. Steady state was defined as the point at which a "levelling off" of the  $\dot{V}O_2$  value occurred, identified by consecutive values within approximately 5% of each other. The net energy cost of locomotion (EC,  $ml\ O_2.kg^{-1}.km^{-1}$ ) was also computed for each velocity plateau. It was defined as the energy required above the resting state to transport the participant's body over one distance unit, with  $EC = (60. (\dot{V}O_2 - \dot{V}O_{2\ rest}). v^{-1})$  where  $\dot{V}O_2$  is the oxygen consumption rate at velocity  $v$  ( $km.h^{-1}$ ), normalized to body mass (kg), and expressed in  $ml\ O_2.kg^{-1}.min^{-1}$  (di Prampero, 1986).  $\dot{V}O_{2\ rest}$  is the oxygen consumption rate at rest set at  $5\text{ ml } O_2.kg^{-1}.min^{-1}$  (Medbo & Tabata, 1989).

#### *Motion data analysis*

Raw joint angle data were filtered using a second-order Butterworth filter with a cut-off frequency of 12 Hz. Joint angles (hip and ankle) were analysed with a custom-made Matlab program in order to select key events using a peak-picking algorithm. Maximum (peaks) and minimal (valleys) values were determined for each gait cycle. Joint amplitude was then defined as the difference between each peak and valley within a cycle. The coefficients of variation of joint amplitudes (standard deviation/mean) were computed for the last 30 gait cycles of each velocity plateau.

## Statistical analysis

Student's t-tests were used to compare the  $\dot{V}O_2max$  and PTS values for non-race walkers and race walkers. To estimate if the nonsignificant effects are negligible or not, we used a Bayesian analysis of variance (ANOVA Rouanet & Lecoutre, 1983) using the PAC software (Lecoutre & Poitevineau, 1992). The participants in the PTS test could be compared by expressing all variables as a function of four treadmill speeds relative to the individual PTS values (e.g., PTS-1 represented one speed interval before the PTS, while PTS +1 represented one speed increment above the PTS). A two-way mixed ANOVA with treadmill speed as repeated measures (PTS-2, PTS-1, PTS, PTS+1) and group as a between factor (RW/NRW) was performed on dependent variables. Our analyses also included post-hoc Tukey's HSD tests for pairwise comparisons. The statistical significance level for all statistical analyses was set at  $\alpha=0.05$ .

A principal component analysis (PCA) was carried out by group (RW and NRW) on independent variables to reduce them to two independent components. Indeed, the measured variables are possibly correlated, meaning that there's some common source of variance among them. PCA aims at identifying a set of uncorrelated variables called *principal components* which are linear combination of the initial variables and which explain the largest part of the total variance. Principal components are ranked ("first", "second") depending on the proportion of the total variance that they explain. For each group, a PCA on angular ankle variability, angular hip variability, energy cost of locomotion (EC) and RPE across all speeds from PTS-2 to PTS+1 was carried out. The four variables for 15 participants over four speeds provided a data set of 60 observations. A varimax rotation solution (with orthogonal components) was adopted with the constraint that two components should be extracted. We considered that a component accounted significantly for a given variable if its corresponding

loading exceeded 0.70, which means that 49% of the variance of the variable was explained by that particular component. Although this criterion might appear conservative, it has been commonly adopted in the generalization of data obtained from a small number of participants (Comrey & Lee, 1992). Statistical analyses were performed with Statistica 7.1 software (Statsoft inc., Tulsa, OK).

## Results

### Participants' characteristics

A Student's t-test showed that the  $\dot{V}O_2max$  values for the non-race walkers and race walkers were not significantly different at  $59.3 \pm 5.6$  and  $60.9 \pm 6.7$  ml O<sub>2</sub>.kg<sup>-1</sup>.min<sup>-1</sup>, respectively. This suggests that the main results described below cannot be interpreted in terms of group differences in the initial level of physical condition or training status (Table 1).

### Preferred Transition Speed

All race walkers used a race walking gait before the transition to running. The race walkers' PTS ( $\pm$  STD) values recorded in the 1st and the 2nd transition tests were  $10.27 \pm 1.31$  km.h<sup>-1</sup> and  $10.43 \pm 1.70$  km.h<sup>-1</sup>, respectively, with no significant difference between these values ( $p > 0.05$ ). For the non-race walkers, the corresponding values were  $7.33 \pm 0.78$  km.h<sup>-1</sup> and  $7.07 \pm 0.69$  km.h<sup>-1</sup>, respectively, with no significant difference between them ( $p > 0.05$ ). We found at the Bayes fiducial probability (guarantee) of 95% that the difference between the two PTS values is lower than 0.62 km/h among racewalkers [ $\Pr(|d| < 0.62) = 0.95$ ] in the parent population, and lower than 0.46 km/h among non racewalkers [ $\Pr(|d| < 0.46) = 0.95$ ]. These results show that the effect of repetition can be considered as acceptable, given that those values are smaller than the intra-group range of PTS values. Finally, nonrace walkers

exhibited on average significantly lower PTS values ( $7.20 \pm 0.06 \text{ km.h}^{-1}$ ) than those for race walkers ( $10.35 \pm 0.28 \text{ km.h}^{-1}$ ) ( $p < 0.01$ ).

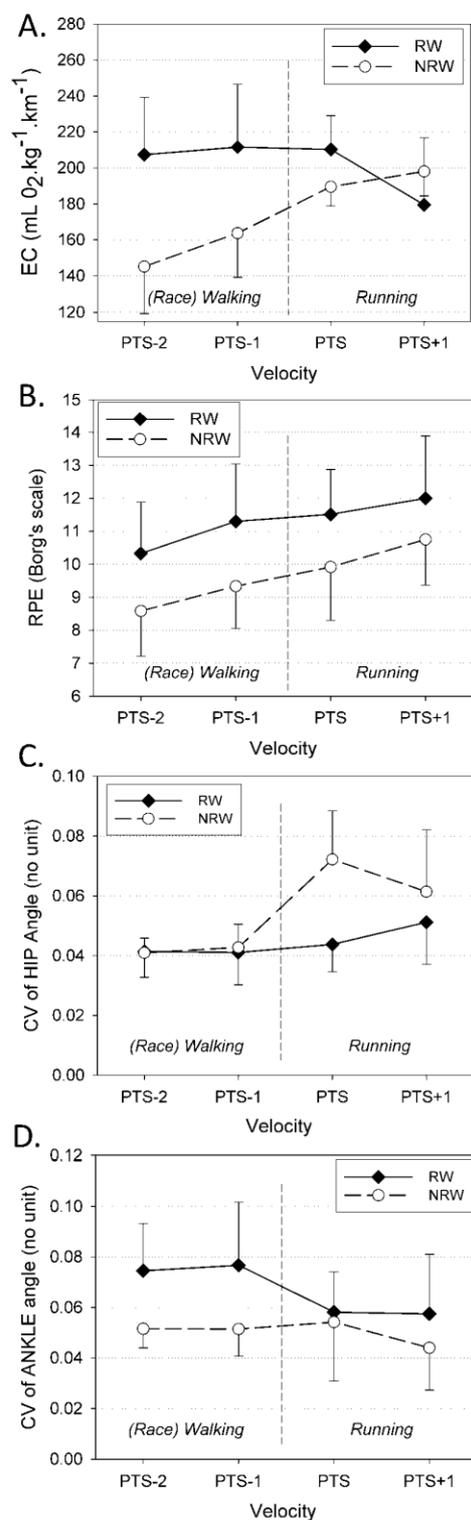


Figure 1: Energy Cost (Panel A), Rate of Perceived Exertion (Panel B), Coefficient of variation of hip angle (Panel C) and Coefficient of variation of ankle angle (Panel D) expressed as a function of treadmill velocity in the PTS test for race walkers (RW) and nonrace walkers (NRW). Treadmill velocity is expressed relative to individual PTS values (PTS refers to the constant velocity interval where transition occurs, PTS-1 refers to the preceding velocity interval, etc.). Error bars represent between-participant standard deviation.

### Energy Cost of Locomotion

An ANOVA carried out on the EC showed a significant main effect of group [ $F(1,13) = 6.59$ ,

$p = .02$ ,  $\eta^2 = .34$ ], a significant velocity effect [ $F(3,39)=4.37$ ,  $p = .01$ ,  $\eta^2=.25$ ] and a significant interaction [ $F(3,39)=14.8$ ,  $p < .0001$ ,  $\eta^2=.53$ ] (Fig. 1A). For the race walkers, the post-hoc test indicated that the EC at the PTS was significantly greater than at PTS+1 but not significantly different from any previous treadmill speed. With regard to the non-race walkers, the EC at the PTS was significantly greater than at PTS-2, but not significantly different from the EC at PTS+1.

### **Rate of Perceived Exertion**

Figure 1B plots mean and standard deviation values of the RPE for the two groups as a function of treadmill velocity. The RPE reported by the race walkers corresponds to a “very light to fairly light effort” according to the RPE scale. An ANOVA yielded only a significant main effect for speed [ $F(3,39)=13.0$ ,  $p < .0001$ ,  $\eta^2=.50$ ].

### **Coefficients of variations in hip and ankle motion amplitudes**

Mean amplitudes of hip and ankle motion during the gait cycle are shown in Table 2 as an indication of the values included in the calculation of the coefficients of variation. Figure 1C plots mean and standard deviation values of the coefficient of variations in hip amplitude. An ANOVA showed a marginal effect of group, with non-race walkers exhibiting higher variability at hip level than race walkers [ $F(1,11)=4.8$ ;  $p=0.05$ ;  $\eta^2=.30$ ], a significant effect of velocity [ $F(3,33)=9.13$ ;  $p < .001$ ;  $\eta^2=.45$ ] and a significant interaction [ $F(3,33)=4.81$ ;  $p < .01$ ;  $\eta^2=.30$ ]. A Tuckey test showed that non-race walkers exhibited a higher variability when running at PTS than when walking at PTS-1. Thus, transition from walking to running brought about a more variable locomotion at hip level. When transitioning from race walking to running, however, there was no significant difference in hip variability.

Figure 1D plots mean and standard deviation values of the coefficient of variations in ankle

amplitude. An ANOVA showed a marginal effect of group, with race walkers exhibiting a somewhat higher degree of variability [ $F(1,12)=4.56$ ;  $p=.05$ ;  $\eta^2=.27$ ], and a significant effect of velocity [ $F(3,36)=2.91$ ;  $p=.05$ ;  $\eta^2=.20$ ].

Table 2 Results of PCA: principal component (PC) loadings, communalities  $h^2$ , % of explained variance

Groups	Variables	PC 1	PC 2	$h^2$
NRW	EC	<b>0,856*</b>	0,038	0,734
	Hip cv	<b>0,789*</b>	0,332	0,733
	Ankle cv	-0,034	<b>0,976*</b>	<b>0,954</b>
	RPE	<b>0,826*</b>	-0,120	0,697
	Explained variance	50,8%	26,5%	
RW	EC	0,513	0,096	0,272
	Hip cv	0,387	<b>0,823*</b>	<b>0,827</b>
	Ankle cv	<b>0,748*</b>	-0,048	0,561
	RPE	-0,521	<b>0,717*</b>	<b>0,785</b>
	Explained variance	31,1%	30,1%	

Note: EC, energy cost of locomotion; Hip cv, coefficient of variation of hip angle; Ankle cv, coefficient of variation of ankle angle; RPE, rate of perceived exertion. \* Component loading  $> 0.70$ .

### PCA results

The PCA was used to summarize common patterns of variation among variables across speeds (PTS-2, PTS-1, PTS, PTS+1). Two principal components were extracted, which accounted for 77.3% and 61.2% of the total variance of variables in the NRW and RW groups, respectively (see Table 2). With a cut off of 0.70 for a variable's inclusion in the interpretation of a component, the main difference between groups was the fact that EC loadings were not significant for any of the two principal components of the RW group. Furthermore, whatever the group, hip variability and RPE were found to be part of the same

principal component whereas ankle variability was from the other principal component.

## Discussion

In the present study, it was expected that the different locomotion behaviors of race walkers and non-race walkers (and associated dependent variables) when faced with an increasing treadmill speed would offer an insight into the determinants of gait transitions. The participants were asked to always use the most comfortable locomotion during the PTS tests (and not the fastest walking speed). Race walkers preferred to race walk instead of run at typically low running speeds, which led to a significantly higher mean PTS than that for the non-race walkers. The PTS of the race walkers was much larger than that found in previous studies (Ziv & Rotstein, 2009), presumably because of our participants' higher skill levels and thus better mechanical efficiency (Hoga et al., 2003). In this discussion, we first comment on the fact that none of the potential transition triggering variables measured in our study appear to be *the* sole key transition trigger. We then discuss how PCA analysis (for each group) offers a new insight into how these variables co-vary when treadmill speed is increased and how a few critical combined variables (principal components) could be determinants in transition triggering.

### *Energy cost, perceived exertion and variability as single triggers*

The variation of energy cost as a response to increasing speed was different for the two groups of participants (see Figure 1A), although they exhibited similar  $\dot{V}O_2max$  levels. Race walkers were able to race walk or run with similar energy expenditure around the transition speed (PTS-1, PTS), whereas an increase from PTS-2 to PTS was present among non-race walkers. This corroborates the results of previous studies that have shown the lower

dependency of energy expenditure of race walking compared with walking, particularly with race walkers well trained in this type of gait (Cavagna & Franzetti, 1981; Hoga et al., 2003). The difference between the two groups is thus more related to the race walkers' capacity to exploit the advantage of this form of locomotion in terms of mechanical efficiency at moderate speeds (mass-spring mechanism) rather than better metabolic power (Hoga et al., 2003; Pavei et al., 2014).

Nonetheless, the two groups shared the fact that there was neither a drastic increase before the transition, nor a systematic post-transition drop in the studied variables. This pattern would have been expected if the minimization of energy expenditure was the driving mechanism (Hreljac et al., 2008). These results are in line with Ziv and Rostein's results (2009) whereby the level of energetic variables did not trigger the transition between gaits. Instead, it could be hypothesized that changing gait occurs to prevent an increase in energy expenditure rather than as a response to excessively high energy expenditure before transition. Indeed, while energy expenditure does not seem to be a sole trigger for transition, this does not preclude its influence on gait transition. The same reasoning could apply for both the perceived exertion variable and gait variability. The participants may have shifted their gait to prevent a rise in the subjective feeling of effort. Among nonrace walkers, the absence of a significant increase in RPE values with speed in the PTS test indicates at least that they followed our instruction to choose a comfortable form of locomotion. For race walkers, the absence of a significant increase in RPE values with speed in the PTS test can be explained by the fact that the participants are accustomed to the activity and have learned their own tolerance level. A comparison of the two groups shows that movement variability seemed to be mainly gait dependent. It may be possible to further test the hypothesis that gait shift may potentially be driven by the prevention of an increase in energy cost, RPE increase or variability increase by using different experimental conditions (e.g., by asking participants to

walk or race walk at speeds for which they preferred to shift to running) and by testing more participants.

*PCA: two groups of variables forming potential transition triggers*

We used a PCA — a multivariate statistical method based on correlation analysis — to identify common sources of variation between metabolic, movement variability and RPE variables. For the two groups, the two PCs could constitute transition triggers, although not to the same extent. Here, the proportion of variance explained by each PC is different in the two groups; it indicates to what extent each PC is sensitive to speed increase. An analysis of which of the studied variables are encompassed in the principal components may be of interest, together with what is common or different between the two groups.

One interesting outcome is that hip angle variability is included in the same principal component as the rate of perceived exertion whatever the group, whilst ankle angle variability constitutes the second principal component. This suggests that perceived exertion could be directly influenced by the increased effort by the hip musculature due to a greater hip angle variability, rather than at the ankle. Recently, several authors have shown that the walk-to-run transition could be the result of a limitation in ankle moment and power generation, resulting in compensation at the hip. In turn, this increases the effort made by the hip muscles (Pires et al., 2014). This makes sense in our study, particularly with race walkers. Indeed, hip motion is thought to be a factor when compensating for full extension of the knee over the stance phase (Pavei et al., 2014). In these conditions, the coupling of hip extensors (during the late swing and early stance phases) and ankle plantar flexors (during the late stance phase) significantly contributes to power generation (Hanley & Bissas, 2013). Here, stressing the leg muscles and/or mechanical constraints leads to a sense of effort. Thus, in both walking and race walking, ankle and hip mechanisms may contribute to gait transition by lowering the

muscular effort of running compared with walking at the walk-to-run transition speed (Farris & Sawicki, 2012; Hanley & Bissas, 2013; Ranisavljev et al., 2014; Riley, Della Croce, & Kerrigan, 2001); however, RPE is more related to hip motion.

The main difference between the groups in our study was that the loading of energy cost was not significant in any of the PCs for the race walkers; however, for the non-race walkers it co-varied with hip variability and RPE in the first principal component. Thus, for non-race walkers, the three variables (RPE, energy cost, hip angle variability) share a common source of variance to form a combined variable (the PC). This may serve as the determinant variable in the transition trigger: twice as much variance produced by an increase in speed is explained by this PC than the second principal component.

Among race walkers, the fact that the loading of energy cost is not significant in either of the two PCs does not mean that energy cost is not an important factor in gait transition for race walkers; rather, it is unrelated to the other studied variables at the studied moderate speeds. Race walkers seem to dissociate energy expenditure from perceived exertion, probably because speeds around PTS do not represent a real physiological effort for these international and national race walkers who are used to training at higher speeds. This lower speed dependency of energy expenditure means that race walkers are more likely to focus on locomotion control (movement variability; focal awareness) rather than physiological sensations.

Thus, our PCA analysis illustrates that instead of looking for a single transition trigger (something that was also difficult to identify in the literature), one should perhaps consider transition triggers as combinations of correlated variables. In our study, the participants used a limited number of these combined variables (i.e., one or two), which are influenced by speed increase, to decide when to shift their gait. The nature and weight of these combined variables

in the decision to shift gait may have been influenced by the participants' expertise and training profiles.

### **Conclusion**

Results show that none of the candidate variables seem to be the sole trigger of gait transition. The present study illustrates, as a first approach, how it may be useful to investigate the determinants of gait transition by looking for groups of correlated biomechanical, physiological and perceptive variables rather than individual variables. In future studies on gait transition, additional neuromechanical or motor behavioral variables already discussed in the literature (e.g., forces, torques, EMG, relative phases) should be involved in any multifactory analyses in order to gain a greater insight into these complex mechanisms, and an integrative approach should be taken.

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**Acknowledgments:** the authors would like to thank elite race walkers, Inés Miraoui and Dr Gilbert Pérés, who allowed this investigation to be carried out in the Sport Medicine laboratory of the University Pierre et Marie-Curie, Pitié Salpêtrière. This study was conducted with non-external funding.