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Article

Gait Variability at Different Walking Speeds

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Abstract: Gait variability (GV) is a crucial measure of inconsistency of muscular activities or body segmental movements during repeated tasks. Hence, GV might serve as a relevant and sensitive measure to quantify adjustments of walking control. However, has not been clarified whether GV is associated with walking speed to exploit effective better coordination level. Fourteen male students (age 22.4 ± 2.7 years, body mass 74.9 ± 6.8 kg, body height 1.78 ± 0.05 m) took part in this study. After three days of walking 1 km each day at a self-selected speed (SS) on asphalt with Apple Watch S. 7 (AppleTM), the participants were randomly evaluated on a treadmill at three different walking speed intensities for 10 minutes each one, at SS-20% / SS+20% of SS, with 5 minutes of passive recovery in-between. Heart rate (HR) was monitored beat-to-beat and normalized as HR%MAX, while the rate of perceived exertion (RPE) (CR-10) was asked after each trial. Kinematic analysis was performed assessing the Contact Time (CT), Swing Time (ST), Stride Length (SL), Stride Cycle (SC) and Gait Variability as Phase Coordination Index (PCI). RPE and HR increased with higher walking speed ($P = 0.005$ and $P = 0.035$, respectively). CT and SC decreased as the speed increased ($P = 0.0001$ and $P = 0.013$, respectively), while ST remained unchanged ($P = 0.277$). SL increased with higher walking speed ($P = 0.0001$). Conversely, PCI was 3.81 ± 0.88 % (high variability) at 3.96 ± 0.47 km·h⁻¹, 2.64 ± 0.75 % (low variability) at SS (4.94 ± 0.58 km·h⁻¹), 3.36 ± 1.09 % (high variability) at 5.94 ± 0.70 km·h⁻¹ ($P = 0.001$). These results indicate that while the metabolic demand and kinematics variables changing linearly with increasing speed, the most effective GV was observed at SS. Therefore, SS could be a new methodological approach to choose the individual walking speed, normalize the speed intensity, and avoid a gait pattern alteration.

Keywords: human locomotion; symmetry; gait analysis; metabolic demand; kinematic analysis

1. Introduction

The analysis of human locomotion during activities such as pedalling [1,2], walking [3,4], race walking [5–7], and running [8–12], exhibits a repetitive and stereotypical movement pattern over time [13–20]. Numerous studies have focused on investigating the variability of the gait cycle paradigm (gait variability, GV) to better understand the bioenergetics and control of the human locomotion [21]. This seemingly simple activity [22–27] involves a complex task [28–34] requiring a precise synergy [35–40] between lower limbs coordination [41–47] and muscle contractions [48–54] in response to both natural and non-natural conditions [55]. As a result, individuals need to continuously explore new strategies [56–63] and promptly adapt the motor task [64–70] to the immediate environment conditions, adjusting their footstep cycle to the most appropriate one.

In walking, stride-to-stride variability [71–77] arises due to the system's constant need [78–82] to adjust inaccurate movements [83]. From neurophysiological point of view, higher variability was associated with poor coordination level, while lower variability indicates better coordination level [84]. Pathological and non-pathological factors have been proven to affect the coordination level. Indeed, Parkinson's disease, aging [55], and individuals with a lower limb injury [85] have been shown to exhibit high variability. Nonetheless, increased variability has been observed in healthy people due to changes in body positions during uphill running [86], alterations in body posture [1] and variations in walking speed [83]. Jordan et al. [83] showed that the better walking coordination

level (i.e., lowest GV) in healthy young females occurred at walking speeds between 100 and 110% of the preferred walking speed. Even though the preferred speed favors better walking coordination [83], most of the studies on GV has used to administer standardized speed on a treadmill [85,87,88]. Anyway, it was showed a divergence about the physiological effort between preferred walking speed on a treadmill compared to the overground [89] suggesting that on a treadmill the preferred walking speed was lower. Therefore, to obtain data that are more representative of daily activities, the GV should be studied at the preferred gait speed determined overground, as treadmill does not fully represent the ground of daily activities. This methodological approach could mitigate the influence of the neurophysiological factors on bioenergetics variables, such as kinematic, kinetic, and motor control aspects. Contrarily, the motorized treadmill [90] provides the advantage of having long duration trials such as gait variability study needed. Indeed, 400 steps are required for an accurate estimation of the step kinematic variability [91] at the constant speed. Certainly, treadmills offer researchers the advantage of precise control over walking speed, enabling extended trials with subjects confined to a limited motion capture space, and the option to connect onboard electronics to a stationary data acquisition system. However, also if Jordan et al. [83] partially clarified that the coordination level trend is speed's dependent, unfortunately the speed (m·s⁻¹ or km·h⁻¹) and metabolic demand (heart rate) were not reported and studied. Furthermore, in that study the preferred walking speed was assessed on the treadmill only. The critical aspect concerning walking speed lies in the fact that each participant exhibits a distinct preferred walking speed. Therefore, the preferred walking speed should be assessed on overground to be more realistic [89], while the gait variability on a treadmill [91] to overcome the GV setting. From this perspective, the aims of this study were: a) to assess individual preferred walking speed in overground setting, b) to determine the metabolic demand and gait variability related to the different walking speeds on a treadmill.

2. Materials and Methods

2.1. Participants

Sixteen male students (age: 23.4 ± 2.7 years, body mass: 74.9 ± 6.8 kg, body height 1.78 ± 0.05 m) voluntarily participated in this study. The participants were healthy without any muscular, neurological, and tendinous injuries and did not report that they were clear of any drug. The diet control in the pre-study was designed to eliminate the risk of any major differences between diets in total protein, carbohydrates, saturated, and unsaturated fats. After being informed on the procedures, methods, benefits, possible risks related to study, all the participants provided their written informed consent. Experimental protocol was approved by the local ethics committee (2-2020) and was performed in accordance with the principles of the latest version of the Declaration of Helsinki.

2.2. Experimental design

The testing sessions were conducted over four different days, separated by a five-day interval. Prior to the testing days, each participant underwent a 25-minute familiarization period with the treadmill (two sessions). During the first two testing days (test-retest for the first test), participants walked outdoor three times at a self-selected speed (SS) on a linear flat asphalt surface for 1 km (average temperature 24.3 ± 1.2 °C, and relative humidity of 18.2 ± 1.5 %) between 10:00 and 12:00 a.m. An Apple Watch S.7 (Apple™, Cupertino, California, USA) was worn to individually determine the SS in km·h⁻¹ [92].

On the last two testing days participants reported to a climate-controlled laboratory (23.5 ± 0.8 °C and 15.1 ± 1.3 % for ambient temperature and relative humidity, respectively). In this session, they were asked to complete after a 10-minute warm-up to walk on a calibrated treadmill (RAM 770 M, Arak, Iran) [90] at three different speeds i) equal to their SS determined in overground (SS); ii) -20% of the SS (SS-20); and iii) +20% of the SS (SS+20). Each speed condition was randomly administered and lasted 10 minutes with 5 minutes of passive recovery in-between. Each participant was asked to wore the same running clothing and shoes (Cat. A3) in all the testing sessions.

2.3. Measurement

During the walking test on a treadmill, HR was recorded continuously (Polar H-10, Kempele, Finland) and normalized as percentage of the maximal heart rate, %HRMAX estimated [93] by (220 - age). Participants also reported their rating of perceived exertion (RPE) on the CR10 scale immediately after completion of each walking speed. Kinematic data were obtained with an OptoGait system (sample rate - 1000 Hz) and a specialized Software (Microgait™, Bolzano, Italy) using a three-lead filter (IN-OUT) [94]. Contact Time (CT), Swing Time (ST), Stride Length (SL), duration of Stride Cycle (SC) and GV, assessed as Phase Coordination Index (PCI), were determined.

The left-right coordination (phase coordination index, PCI) of walking gait was assessed according to Plotnik and coll [13], normalizing the step time with respect to the stride time. The former relates to the time interval between a heel strike and the one of the contralateral leg whereas, the latter relates to the time interval between a heel strike and the consecutive one of the same leg. The normalization of step time with respect to the stride time determines the phase of the i -th stride (\emptyset_i) which represents an index of bilateral coordination [13]. To preserve uniformity across all participants with possible different dominance, firstly we calculated the average values of ST for both legs and used the leg with the higher ST as the reference for gait cycles. Successively, \emptyset_i values for the other leg were computed as:

$$\emptyset_i = 360^\circ \times \frac{t_{Si} - t_{Li}}{t_{L(i+1)} - t_{Li}} \quad (1)$$

where t_{Si} and t_{Li} denote the time of the i -th heel strike of the legs with the short and long ST, respectively, and $t_{L(i+1)} > t_{Si} > t_{Li}$. The factors at the denominator of (1) relate to ST of the leg with the longest ST. Lastly, 360 was used to transform the variable into degrees [55]. A \emptyset value of 180° indicates a successful walking symmetry with step time being half of the gait cycle for each step. The GV encompasses the evaluation of the accuracy and consistency of phase generation and serves as the primary outcome. The accuracy level in phase generation, measuring how closely the series of generated phases align with the value 180° , was assessed by calculating the mean value of the absolute differences between the phase at each stride and 180° . This measure is denoted as \emptyset_ABS :

$$\emptyset_ABS [^\circ] = \overline{|\emptyset_i - 180^\circ|} \quad \overline{|\emptyset_i - 180^\circ|}$$

To evaluate the level of consistency in phase generation across all strides for each participant, the coefficient of variation of the mean of \emptyset was also determined. This consistency is represented as \emptyset_CV [%]. Lastly, to compensate for the association between \emptyset_ABS and \emptyset_CV , the phase coordination index (PCI) was obtained as $PCI = \emptyset_CV + P\emptyset_ABS$, where $P\emptyset_ABS = 100 \times (\emptyset_ABS/180)$. Further details about the association between \emptyset_ABS and \emptyset_CV can be found in Plotnik and coll [13]. Notably, the PCI, provides insights into both the accuracy and consistency of phase generation.

2.4. Statistical analysis

Results are expressed as mean \pm standard deviation (SD). Shapiro-Wilk test was used to verify the normality of the distribution. The reliability of the SS and PCI was assessed by an Intra-Class Correlation Coefficient (ICC) and classified as poor, if < 0.05 ; moderate, if between 0.50 and 0.75; good, if between 0.75 and 0.9 and excellent, if > 0.9 , according to Koo and Li [95]. To assess differences for %HRMAX, RPE, CT, ST, SC, SL, PCI, \emptyset_CV , \emptyset_ABS , \emptyset over the 3 different walking conditions (SS-20/SS/SS+20%), a one-way, repeated-measures analysis of variance (RM-ANOVA) was used. When significant F-value was found, post-hoc analysis (LSD) between conditions was performed. The ANOVA effect size was also calculated (partial eta squared η_p^2) and classified as small (< 0.06) medium (0.06 – 0.14); and large (> 0.14) [96]. The significance level was fixed as $P \leq 0.05$. All the analysis were conducted using Statistical Package for Social Science software (V. 21.0, IBM SPSS Statistics, Chicago, IL, USA).

3. Results

The SS was 4.94 ± 0.58 (min/max: 4.00 - 6.20) $\text{km}\cdot\text{h}^{-1}$. The speed during SS-20 was 3.96 ± 0.47 (min/max: 3.20 - 5.00) $\text{km}\cdot\text{h}^{-1}$ and the speed during SS+20 was 5.80 ± 0.73 (min/max: 4.80 - 7.44) $\text{km}\cdot\text{h}^{-1}$. RM-ANOVA showed differences among the three walking speeds for RPE (0.84 ± 0.61 , 0.97 ± 0.68 , 1.78 ± 0.83 a.u. in SS-20, SS, SS+20%, respectively) as well as HR (50.95 ± 4.50 , 52.85 ± 5.27 , 56.70 ± 5.79 %HR_{MAX}, in SS-20, SS, SS+20%, respectively with $F_{1,12} = 24.680$, and $\eta_p^2 = 0.655$ (ES: Large) with $P = 0.005$ / $F_{1,12} = 43.785$, and $\eta_p^2 = 0.814$ (ES: large) with $P = 0.035$; respectively.

CT and SC decreased as the speed increased (Table 1 with post-hoc analysis) $F_{1,12} = 8.232$, and $\eta_p^2 = 0.388$ (ES: Large) with $P = 0.013$ / $F_{1,12} = 4.974$, and $\eta_p^2 = 0.277$ (ES: Large) with $P = 0.044$; respectively; while ST unchanged ($F_{1,12} = 0.898$, and $\eta_p^2 = 0.065$ (ES: Medium) with $P = 0.086$). SL increased at the speed increased ($F_{1,12} = 1,146.447$, and $\eta_p^2 = 0.990$ (ES: Large) with $P = 0.0001$). Conversely, the bilateral coordination (Table 2 with post-hoc analysis) data showed a parabolic trend. ANOVA showed large differences for: \emptyset (Figure 1) with $F_{1,12} = 16.360$ and $\eta_p^2 = 0.561$ with $P = 0.001$; PCI (Figure 2) with $F_{1,12} = 17.731$ and $\eta_p^2 = 0.577$ with $P = 0.001$; \emptyset_{CV} with and $\eta_p^2 = 0.833$ with $P = 0.001$; \emptyset_{ABS} with $F_{1,12} = 17.701$ and $\eta_p^2 = 0.577$ with $P = 0.001$. ICC for PCI was 0.905 (CI 95 %: 0.704 - 0.969). The ICC for SS was 0.998 (CI 95 %: 0.994 - 0.999).

Table 1. Footstep variables on the three different walking speed (SS-20/SS/SS+20).

Variables	SS-20	SS	SS+20
CT (s)	0.80 ± 0.07 ††	0.68 ± 0.06 §	0.59 ± 0.06
ST (s)	0.40 ± 0.03	0.39 ± 0.03	0.40 ± 0.03
SL (cm)	131 ± 11 ††	147 ± 10 §	163 ± 11
SC (s)	1.14 ± 0.21 †	1.08 ± 0.07	0.99 ± 0.07

Contact Time (CT); Swing Time (ST); Stride Length (SL); Stride Cycle (SC) are reported as mean and standard deviation (SD). significant ($P < 0.05$) differences between SS-20/SS are denoted as “†”, SS-20/SS+20 as “††”, SS/SS+20 as “§”.

Table 2. Effects of the three different walking speed (SS-20/SS/SS+20) on the bilateral coordination parameters.

Variables	SS-20	SS	SS+20
PCI (%)	3.81 ± 0.88 †	2.64 ± 0.75 §	3.36 ± 1.09
\emptyset_{CV} (%)	2.04 ± 0.47 †	1.45 ± 1.83 §	1.83 ± 0.58
\emptyset_{ABS} (deg)	1.77 ± 0.42 †	1.19 ± 0.33 §	1.55 ± 0.51
\emptyset (deg)	182 ± 0.6 †	181 ± 0.3 §	181 ± 0.7

Note: data are expressed as mean and SD; significant ($P < 0.05$) differences between SS-20/SS are denoted as “†”, SS-20/SS+20 as “††”, SS/SS+20 as “§”.

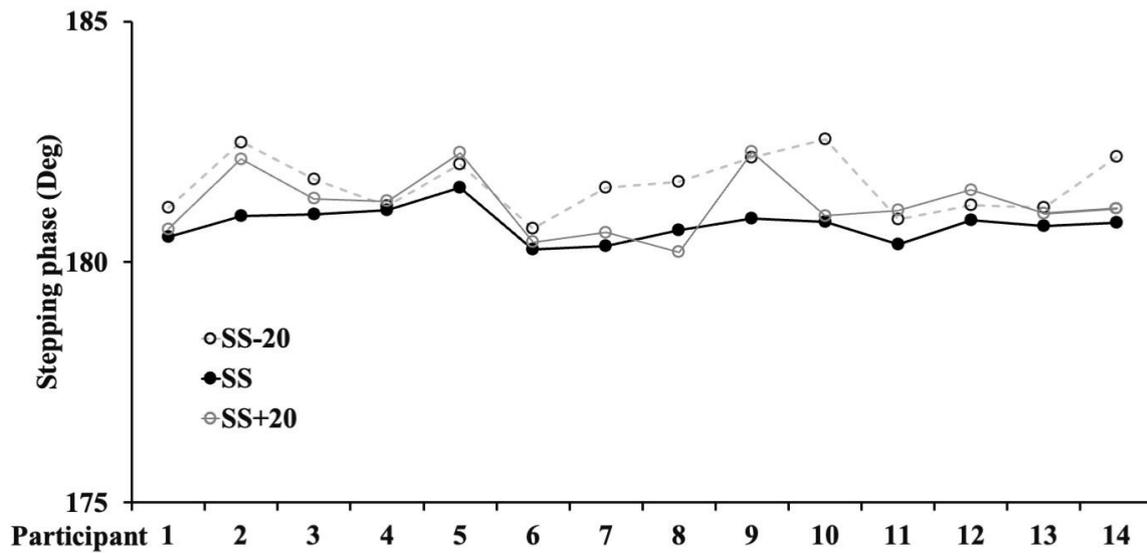


Figure 1. Stepping phase value for each participant on three different speed.

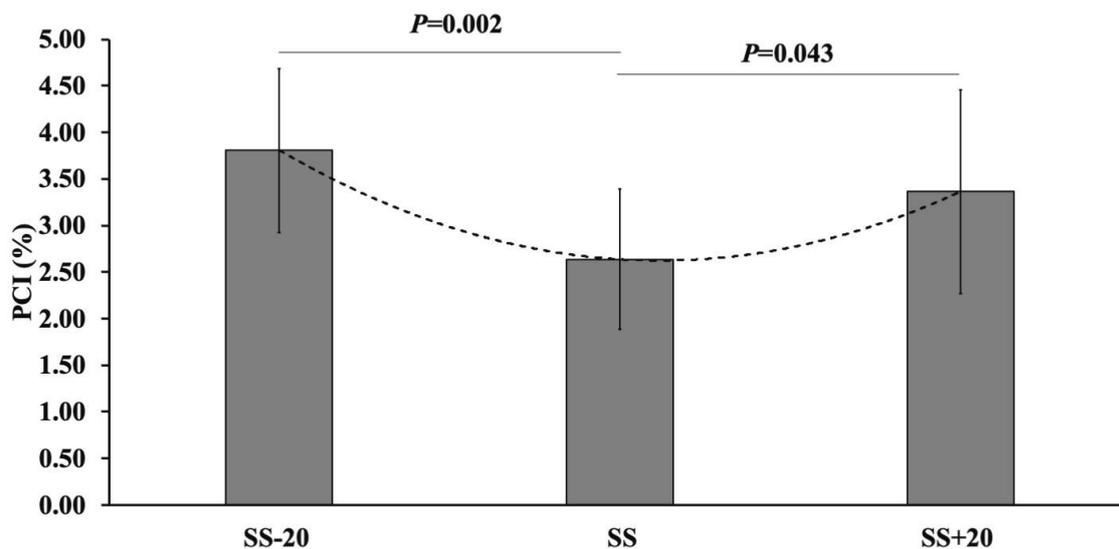


Figure 2. Bar chart demonstrating the PCI differences between the three different speed.

4. Discussion

This study represents the first attempt to assess the individual preferred walking speed in 1 km overground, evaluating the metabolic demand and the gait variability on a treadmill. Our findings revealed a self-selected speed range between 4.00 and 6.20 km·h⁻¹, which is a crucial finding with significant implications for future research on walking gait in healthy individuals. Previous studies have reported differences in physiological and perceptual responses when comparing treadmill walking to overground walking for self-selected speed attainment [24,25]. However, the practicality of outdoor walking is often hampered by various environmental obstacles, such as safety concerns and adverse weather conditions, prompting the use of treadmills in various physical activity programs as an alternative [93]. Nonetheless, the ecological validity of treadmill walking as a substitute for overground walking remains a relevant question that requires further investigations. Unfortunately, limited research has been dedicated to addressing this inquiry. Parvataneni et al. [26] discovered that treadmill walking at a self-selected pace demands a higher metabolic effort compared to overground walking, possibly due to increased co-contraction of agonist and antagonist muscles.

The second aim of this study was to assess the metabolic demand at different walking speeds. At self-selected walking speed the metabolic demand was 52.85 ± 5.27 %HRMAX and, increased/decreased concurrently with the speed. In the current study, participants reported RPE ranging from 1 to 2, regardless the environment setting, according to previous laboratory-based studies that employed self-paced protocols [97,98]. Our investigation revealed significantly higher RPE during the SS+20 on the treadmill session. According to Foster's model of effort continua, this disparity in exertional perceptions [99] can be attributed to the moderate physiological demands associated with the walking speed.

The third aim was to determine the gait strategies variability at different speeds in the neighborhood of the overground self-selected speed. The kinematic data as CT (SL and SC showed a strong linear correlation when the speed increased (Table 1). Conversely, the motor coordination level showed a U-shaped behavior, Figure 2). Therefore, the gait variability was not conditioned from both of fatigue effects and/or by physiological efforts. Indeed, our investigation showed a U-shaped function (Figure 2) about the PCI as gait variability; thus, the PCI was higher (low coordination) at SS-20 (3.81 ± 0.88 %) and SS+20 (3.36 ± 1.09 %) compared to the SS (2.64 ± 0.75 %) with $P = 0.001$. The same parabolic U-shaped function trend (Table 2) was found for \emptyset_{CV} , \emptyset_{ABS} , \emptyset according to Plotnik et al. [55].

A similar U-shaped trend in gait variability, analyzed using long-range correlation through detrended fluctuation analysis, has been observed in both running and walking gaits for female participants [14], although physiological effort measurements were not included. In both walking and running conditions Jordan et al. [14,29] found that the lowest gait variability was observed at 100/110% of the preferred walking speed and 100% of the running speed, respectively. Therefore, the PCI and the long-range correlation using detrended fluctuation analysis might be equivalent in assessing gait variability from a methodological standpoint. However, the PCI analysis provides more comprehensive information regarding gait variability, including the accuracy and consistency of phase generation (\emptyset_{CV} , \emptyset_{ABS} , \emptyset). These metrics quantify the ability of young males to coordinate left-right stepping on flat terrain at different speeds and evaluate the precision and coherence of the gait pattern [13].

These metrics was able to quantify the ability of young male to coordinate left-right stepping on flat at different speeds. Simultaneously, the PCI assesses both the precision (Table 2) of anti-phase coordination and the coherence of the gait pattern [55]. Consider that the lower limb during the walking gait is not constrain as in pedaling cycle [1] we think that is more appropriate to consider all kinematic parameters (stride cycle, the stride length, the swing time, and the contact time) as in PCI, compared to long-range correlation using detrended fluctuation analysis where is used the stride cycle, only.

5. Conclusions

Our study demonstrated that walking at a specific, self-selected pacing requires the participant to continuously adjust the force produced and its timing relative to the foot position [1]. Reasonably, When the timing or the module of the force is not applied appropriately, an unwanted acceleration or deceleration of the lower limb occurs, inducing a fluctuation in cycle duration. It is possible that unusual riding positions change cycling variability due to mechanical factors [83]. Therefore, an increase in the number of corrections of the leg/foot velocity through timing activation of lower leg muscles is expected to increase gait variability, possibly as a function of walking speed. The gait variability is believed to reflect the need of central pattern generators to correct timing activation of different muscles throughout the step cycle. As such, it is possible that the increase of the variability observed in SS-20 and SS+20 reflects a higher number of corrections during the cycle due to the position [88,100]. This is also suggested by Marck et al. [101] which observed that restricting arm movements altered hip movement variability during walking. In conclusion, the metabolic demand and kinematics variables changed linearly when the speed increased. The walking gait coordination followed U-shaped curves as a function of walking speed, the better was at self-selected speed in healthy young males. These finding support the hypothesis the reduces PCI at SS is reflective of

enhanced stability of these speeds. Therefore, SS could be a new methodological approach to choose the individual walking speed in overground, to normalize the intensity speed, to avoid a gait pattern alteration.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest; or in the decision to publish the results”.

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