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Uphill walking at iso-efficiency speeds

AUTHORS: Mirjana Milic[1], Marko Erceg[1], Stefano Palermi[2], Enzo Iuliano[3], Marta Borrelli[4], Emiliano Cè[4], Fabio Esposito[4], Johnny Padulo[4]

[1] Faculty of Kinesiology, University of Split, Split, Croatia
[2] Human Anatomy and Sport Medicine division, Department of Public Health, University of Naples "Federico II", Naples, Italy
[3] Faculty of Psychology, eCampus University, Novedrate, Italy
[4] Department of Biomedical Sciences for Health, Università degli Studi di Milano, Milan, Italy

Corresponding author:
Johnny Padulo
Department of Biomedical Sciences for Health, Università degli Studi di Milano, Via Antonio Kramer 4/A, 22060, Milan, Italy
E-mail: sportcinetic@gmail.com

ABSTRACT: Uphill walking gait has been extensively studied, but the optimal uphill speed able to enhance the metabolic demand without increasing fatigability has so far received little attention. Therefore, the aim of this study was to assess the metabolic/kinematic demand at constant speed (6 km·h^{-1} G0 level, G2 2% uphill, G7 7% uphill) and at iso-efficiency speeds (G2IES 5.2 km·h^{-1} 2% uphill and G7IES 3.9 km·h^{-1} 7% uphill). For this aim, physically active women (n:24, Age 33.40 ± 4.97 years, BMI 21.62 ± 2.06 kg/m^{-2}) after an 8-min warm-up were studied on a treadmill for 10′ for every walking condition with a 5′ rest in between. Average heart rate (AVG-HR), rating of perceived exertion (RPE) and kinematic variables (stance time, swing time, stride length, stride cycle, stride-length variability, stride-cycle variability and internal work) were studied. Modifications in stance time, stride length and stride cycle ($p<0.005$), and lower internal-work values ($p<0.001$) occurred in G7IES in comparison to the other conditions. Swing time was significantly modified only in G7IES compared to G0 and G7 ($p<0.001$ and $p<0.005$, respectively). Stride-length variability and stride-cycle variability were higher in G7IES compared to the other conditions ($p<0.001$). G7 induced the highest AVG-HR ($p<0.005$) and RPE ($p<0.001$) compared to the other conditions. This study demonstrates that by applying the equation for uphill walking gait, it is possible to maintain a similar metabolic demand and RPE at iso-efficiency speeds during uphill compared to level walking, inducing at the same time a modification of the kinematic parameters of walking gait performed at the same slope condition.

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INTRODUCTION

Level walking is a rhythmic, dynamic and aerobic physical activity that provides multifactorial benefits [1, 2] with minimal adverse effects [3]. Indeed, it is usually prescribed by physicians and health operators as the primary form of activity to improve physical fitness [4]. Also, it was advised to perform 10,000 steps per day to prevent cardiovascular diseases [5]. In recent years, uphill race walking and running has attracted interest for several reasons [6, 7]. Uphill walking is a challenging and very common task in daily life activities [8]. Many people use uphill walking to activate their lower limb muscles to a higher extent than level walking, due to the increase of mechanical work [9]. This characteristic leads to a higher metabolic and biomechanical demand in uphill walking compared to level walking at constant speed [10, 11, 12]. From a metabolic point of view, a previous study reported an increase in the metabolic demand of ~0.24 × slope (in %) in uphill walking above the energy cost of level walking (3.20 J/m/kg) [13]. This was explained by an increase in the mechanical internal work [14] and by higher lower limb muscle activity [15] during uphill walking. However, the metabolic increment is just a part of the changes induced by uphill walking/running: in fact, previous investigations also reported an alteration in some kinematic gait parameters such as a decrease in stride length and an increase in stride frequency, as a function of the slope [6, 7]. For these reasons, a study analysing the effects of uphill walking/running should overall evaluate both metabolic and mechanical variables of gait locomotion.

The relative weight of each aforementioned variable could outline different scenarios: on one hand, the higher metabolic demand required during uphill walking could induce a greater improvement in physical fitness [16]; on the other hand, the higher metabolic and biomechanical demands of uphill walking can be challenging for people with a walking impairment, such as community-dwelling old adults [17]. This could likely induce greater muscle fatigability and possibly disincentivize people from performing uphill walking training. Therefore, it is necessary to determine which uphill walking speeds can induce a similar metabolic demand compared to level walking. This condition would combine the benefit of uphill walking while limiting its side effects, i.e., greater muscle fatigability [18], to provide easier walking for people with walking impairment. To the authors' best knowledge, no previous studies have explored the metabolic demand and the kinematic analysis of uphill walking. For this purpose, we assume that, given the increase in the energetic cost of different uphill walking (~ 0.24 J/m/kg × slope (%)) [13], it would be possible to calculate the iso-efficiency speed (IES) on each slope (%) by monitoring the metabolic demand (i.e., heart rate, HR) without increasing the metabolic demand compared to level walking. Indeed, to reach the same metabolic demand in uphill compared to level walking, the IES approach will be used as in race walking and running adjusted for walking gait [19, 20]. Accordingly, the aim of this study was to assess the metabolic demand at constant speed (i.e., the same speed on different slopes) and at IES (i.e., the same metabolic demand on different slopes) related to the footstep analysis.

MATERIALS AND METHODS

Participants

Twenty-four physically active women participated in this study (age 33.40 ± 4.97 years; body mass 63.05 ± 9.04 kg; height 1.70 ± 0.07 m; BMI 21.62 ± 2.06 kg/m^{-2}; training experience 6.10 ± 2.25 years in physical fitness). Participants with muscular, neurological or tendon injuries were excluded from the study. The group was homogeneous regarding training status, in which none of the participants underwent any endurance strenuous activity and/or resistance training outside of their normal endurance training protocol. The experimental protocol was approved by the local Ethical Committee. After being informed of the procedures, methods, benefits and possible risks involved in the study, each participant reviewed and signed an informed consent form to participate in the study in accordance with the ethical standards of the latest Declaration of Helsinki principles.

Experimental setting

Testing was conducted in a Sport Performance Laboratory. All participants were in good health at the time of the study. During this study, in order to better standardize the slope and the velocity, tests were performed on a motorized treadmill (Cosmos HP, Nussdorf-Traunstein, Germany). The percent grade was equal to the tangent [*theta*] × 100. The treadmill was calibrated before each test according to the instructions of the manufacturer and regularly checked after the tests [21]. All participants wore running shoes (Cat. A3) and performed a standardized eight-minute warm-up to familiarize themselves with the treadmill, which consisted of walking at 5 km·h^{-1} [21]. Each participant was tested in five different sessions, corresponding to five different conditions, separated by at least three days of rest. The order of execution of the five sessions was randomly assigned (Latin Square) and the five conditions were: walking on a level gradient (G0, 0% slope and 6 km·h^{-1} speed), walking on a 2% slope (G2, 2% slope and 6 km·h^{-1} speed), walking on a 2% slope at IES (G2IES, 2% slope and 5.2 km·h^{-1} speed), walking on a 7% slope (G7, 7% slope and 6 km·h^{-1} speed) and walking on a 7% slope at IES (G7IES, 7% slope and 3.9 km·h^{-1} speed). Tests lasted 10 minutes for each walking condition. The IES was calculated according to the method described by Padulo et al. [19, 20], updated for walking and calculated at 2% and 7% as 5.2 and 3.9 km·h^{-1} respectively, depending on each subject's fitness and the gradient. The IES for each participant at 0% gradient (G0) was fixed at 6 km·h^{-1} as the common velocity for walking gait corresponding to an energy cost (Cr) of 3.20 J/m/kg [13] and confirmed by a preliminary test as comfortable speed based on the physiological/psychophysiological data (HR and RPE). Furthermore, according to previous data [13], the increase of Cr as a result of a level gradient is:

$$\textbf{Cr on slope} = \mathbf{0.24 \times slope\ (\%) + Cr_0}$$

where Cr_0 is the Cr at level gradient (0%).

As mentioned above, as the oxygen uptake ($\dot{V}O_2$) is proportional to the energetic cost and velocity, the velocity (IES) was calculated for each gradient using the following equation:

$$\dot{V}O_2 = [Cr_0/(21(J/min) \times (IES_0/0.06\ (m/min))]$$
$$IES\ (km \cdot h^{-1}) = [(\dot{V}O_2(kJ/min/kg) \times 21\ (J/l) \times 0.06\ (m/min)/(0.24\ (Cr) \times slope\ (\%) + Cr_0)]$$

Measurements

The HR was recorded throughout the experiment and an average was computed during the full 10 minutes for each slope/velocity condition (Suunto Memory-belt, Suunto Oy, Vantaa, Finland) and thereafter normalized as percentage (%HRmax) of the theoretical maximal heart rate value calculated with Tanaka formula (208–0.7×age [22]). Furthermore, the average of %HRmax was calculated (and named AVG-HR). Moreover, the participants indicated their rating of perceived exertion (RPE) using the category rating-10 (CR-10) scale modified by Foster et al. [23] immediately at the end of each walking set. Considering that the walking gait variability requires many stride cycles (up to 8′) at 1,000 Hz as the sample rate, we used OptoGait (Microgait Bolzano, Italy) [24] on the treadmill. The following kinematic variables were calculated on 10′ for each one: the duration of the stance phase (STANCE; in seconds); the duration of the swing phase (SWING; in seconds); the stride length (STRIDE; in centimetres); the number of strides performed in a second (CYCLE; in seconds). For each walking condition, the coefficient of variation of the length of the stride (STRIDE-CV; in percentage) and the coefficient of variation of the stride cycle (CYCLE-CV; in percentage) were also calculated to provide walking variability indexes [21]: the coefficient of variation were calculated as ((SD/mean) ×100). After one week the whole trial was repeated to assess the reliability of the measurements.

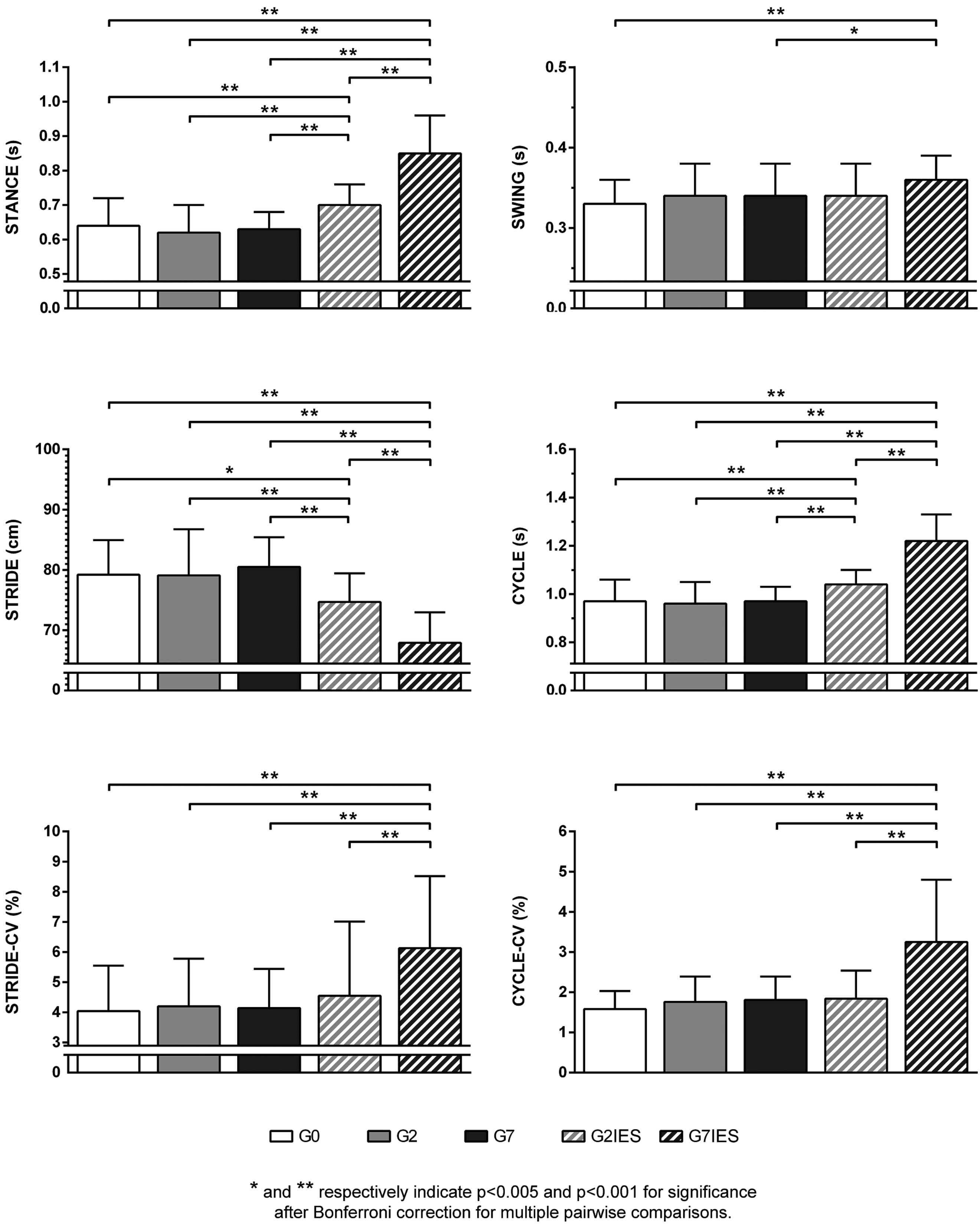

FIG. 1. Kinematic analysis of five different walking gaits

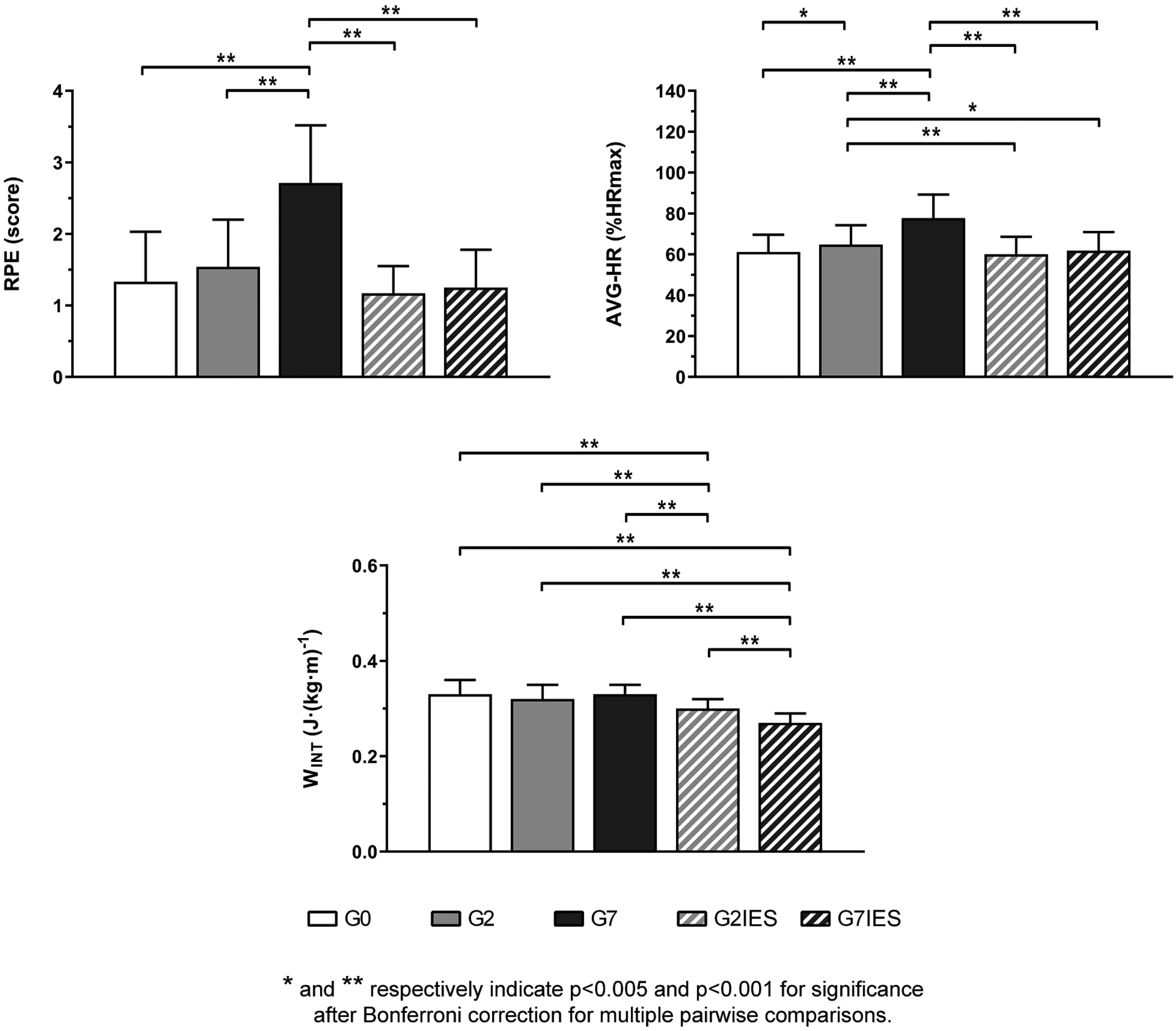

FIG. 2. Metabolic demand, rate of perceived exertion and internal work for five different walking gaits

Internal work

We calculated the internal work (W_{INT}) using the following equation [14]:

$$W_{INT} = \text{stride cycle} \times v \times (1+(DF \times (1\text{-}DF)^{-1})^2) \cdot q$$

where the stride cycle is in seconds, v is the speed in m·s^{-1}, DF is the *duty factor* that is the deflection of the duration of the stride period when each foot is on the ground and q is the value of 0.1 referring to the inertial properties of the oscillating limbs.

Statistical analysis

Primarily, the Shapiro-Wilk test was used to assess the normality of the variables. For the variables in which normality was satisfied, a repeated measures analysis of variance (RM-ANOVA) was used to assess overall significant differences between the five gait conditions (within factor of the analysis: G0 vs. G2 vs. G7 vs. G2IES vs. G7IES). Bonferroni post hoc with multiple testing correction was successively used to evaluate the differences in the pairwise comparison when a significant p-value was detected. Partial eta squared (η^2p) was also calculated as the effect size index. For the variables in which normality was not satisfied, the non-parametric Friedman test was used to assess overall significant differences between the five conditions. In this case, the Wilcoxon test with Bonferroni multiple testing correction was employed for post-hoc analysis when a significant p-value was detected. For this analysis, the effect size was determined using Kendall's W test. Bonferroni correction for multiple tests was applied both for the main and for post-hoc analyses. In particular, Bonferroni correction applied to main analyses indicated that a p<0.005 was needed for statistical significance due to the dependent variables. Bonferroni correction applied to the post-hoc analysis indicated that p<0.005 was instead necessary due to the pairwise comparisons between the five conditions (10 pairwise comparisons). Finally, the reliability [25] of the procedure was evaluated by the intra-class correlation coefficient (ICC) computed with a two-way random model (consistency). All analyses were performed with the statistical software SPSS 20 (IBM Corporation, Chicago, IL, USA).

RESULTS

ICC showed excellent reliability for the variable RPE with $ICC_{(2,2)} = 0.911$, whereas the variables AVG-HR, STANCE, STRIDE, CYCLE, W_{INT} and STRIDE-CV showed good reliability with $ICC_{(2,2)}>0.750$ and <0.900. Finally, the variables SWING and CYCLE-CV showed moderate reliability with $ICC_{(2,2)} = 0.524$ and = 0.685, respectively.

The RM-ANOVA showed that SWING time significantly differed between the five conditions ($F_{(3,69)} = 5.076$; p = 0.003; $\eta^2 p = 0.181$). Similarly, the non-parametric Friedman test revealed significant differences between the five gait conditions (Figure 1) for STANCE time ($\chi^2_{(4)} = 68.510$; p<0.0001; Kendall's W = 0.714), STRIDE length ($\chi^2_{(4)} = 62.133$; p<0.0001; Kendall's W = 0.647) and stride CYCLE ($\chi^2_{(4)} = 67.833$; p<0.0001; Kendall's W = 0.707). The post-hoc analyses showed that both G2IES and G7IES conditions produced a significant increase of STANCE and CYCLE variables, and a significant reduction of STRIDE variable compared with one of the other conditions including the comparison G2IES vs. G7IES (all with at least p<0.005). SWING was significantly modified only in G7IES compared to G0 and G7 (respectively with p<0.001 and p<0.005).

The Friedman test performed on STRIDE-CV showed (Figure 1) significant differences between conditions ($\chi^2_{(4)} = 38.811$; p<0.0001; Kendall's W = 0.462) and similarly the same analysis performed on CYCLE-CV (Figure 1) revealed significant differences between conditions ($\chi^2_{(4)} = 35.714$; p<0.0001; Kendall's W = 0.425). The post-hoc analysis showed that STRIDE-CV and CYCLE-CV were both significantly higher in G7IES compared to each of the other conditions (at least p<0.001).

The Friedman test performed on W_{INT} also showed significant differences between the five conditions ($\chi^2_{(4)} = 70.067$; p<0.0001; Kendall's W = 0.730), and the post-hoc analysis showed lower values of W_{INT} compared to each of the other conditions with at least p<0.001, including the comparisons G2IES vs. G7IES.

Finally, regarding the metabolic parameters, the RM-ANOVA showed significant differences between the five conditions for AVG-HR ($F_{(2,55)} = 87.008$; p<0.0001; $\eta^2 p = 0.791$) and the Friedman test performed on RPE also revealed significant differences between the five conditions ($\chi^2_{(4)} = 71.813$; p< 0.0001; Kendall's W = 0.748). Post-hoc analysis indicated that both G2 and G7 conditions induced a significantly higher value of AVG-HR (at least p<0.005) compared to each of the other conditions, including the comparisons G2 vs. G7, but the RPE was significantly higher only in the G7 condition compared with each of the other conditions (at least p<0.001). For further clarity, the results of the post-hoc analyses are presented in Figure 1 (gait parameters) and Figure 2 (W_{INT}, AVG-HR and RPE).

DISCUSSION

In this study, we investigated the effects of five walking gait conditions on a treadmill, 0% (on level at 6 $km \cdot h^{-1}$), 2% uphill (constant speed 6 $km \cdot h^{-1}$), G2IES (IES 5.2 $km \cdot h^{-1}$), 7% (constant speed 6 $km \cdot h^{-1}$) and G7IES (IES 3.9 $km \cdot h^{-1}$), on temporal gait kinematics and metabolic demands related to the RPE. The present findings demonstrate that by applying the equation for uphill walking gait, it is possible to maintain a similar metabolic demand and RPE during IES in uphill compared to level walking. At the same time, uphill walking at IES increased the stride cycle (≈7 and 26% at G2IES and G7IES, respectively), stance time (≈10 and 34% at G2IES and G7IES, respectively), swing time (≈10% at G7IES), stride and cycle CV (≈8 and 26% at G2IES and G7IES, respectively, whereas stride length and W_{INT} decreased (≈8 and 23% at G2IES and G7IES, respectively) compared to the level walking.

As far as the metabolic demand and RPE are concerned, the present findings demonstrate that it is possible to precisely modulate the speed of uphill walking in order to obtain the same amount of metabolic demand (G0, G2IES and G7IES showed no significant differences in AVG-HR as shown in Figure 2). Conversely, when the participants walked at constant speed, the metabolic demand responses increased according to the gradient (Figure 2; G2 and G7 the AVG-HR responses increased for ≈6 and 27% compared to the level walking with $p<0.05$ in both cases), in line with other studies [13, 16, 26]. Moreover, the RPE at IES was lower compared to the constant-speed condition, demonstrating the ease of walking without any discomfort and, indeed, the decreased mechanical internal work.

The increased gait variability (Figure 1) in uphill at IES as the coefficient of variation of the stride length (STRIDE-CV was significantly higher in G2IES and G7IES compared to the level walking) could be explained by the decreased stride length (G2IES and G7IES both showed significantly lower values compared to G0). On the one hand, a decreased stride length from the natural gait provided an alteration during the uphill walking task involving the coordination of the lower limbs and a shift in the organization of physiological muscle responses. For this task, the women investigated in this study at IES explored the immediate environment and corrected the stride time (stride-to-stride); therefore stride-to-stride variability emerges as an effect of body systems correcting movement errors [27]. Furthermore, the stride length variability reflects the need for the Central Pattern Generator to time the activation of different lower limb muscles during the stride cycle [28]. Accordingly, increased gait variability in uphill walking at IES is due to an increased number of corrections during the stride cycle, as suggested by Marks [29] in relation to the restriction of arm movement related to hip movement variability during the walking gait. On the other hand, it is to be taken into consideration that, despite a similar metabolic demand, the increased step duration, decreased step length, and increased variability occurring at G2IES and G7IES could reduce walking stability, thus possibly increasing the risk of falling.

This result corroborates the findings of Leurs et al. [30], which suggest that the proportion of specific limb segments may play an essential role in the kinematics and energetics of walking. This study provides clear evidence that walking on different slopes but with IES makes it possible to change freely the kinematic parameters without modifying the metabolic demand. This could allow slope training to also be used in those subjects who usually avoid it to reduce cardiac load. Moreover, uphill walking has been shown to effectively improve glucose tolerance and most of the measured lipid markers in pre-diabetic men [31]. Furthermore, subjects could obtain a coordination benefit induced by the modification of kinematic parameters (stride and cycle), while maintaining metabolic and cardiovascular stress. In fact, the negative effect of metabolic stress upon several functions of the human body [32, 33] is known, so it is very important to keep it as low as possible.

Our findings reinforce the 'iso-efficiency speed' concept as a practical and valid strategy in the design and conceptualization of fitness programmes. From a wider perspective, the iso-efficiency method could also be relevant to some medical and rehabilitation fields. Obtaining musculoskeletal and fitness advantages while avoiding increased metabolic and cardiovascular costs should be desirable in some population subsets. From a medical perspective, some exercise stress protocols have been commonly used to investigate athletes and to conduct pre-participation screening. The purpose of these procedures is to increase the metabolic costs and cardiovascular demand to reveal pathological conditions. Several methods and types of equipment, i.e., cycle ergometers [34], arm ergometers [35], treadmills and specific protocols [36], have been widely used, and they aim to increase ergometer resistance or the slope and velocity of the treadmill to 'stress' the cardiovascular system and maximize the metabolic demand. However, the concept of iso-efficiency has a different objective and has been investigated less. The main objective of this approach is to obtain the highest performance benefits while lowering or at least not increasing the metabolic cost of a specific task. Therefore, the iso-efficiency concept could be easily applied in fitness, in the early phases of return-to-sport activity and in the early reconditioning stage of cardiovascular rehabilitation. Further studies could widen its application beyond uphill walking (i.e., managing the resistance parameter of ergometers to obtain musculoskeletal advantages without increased metabolic and cardiovascular costs in indoor scenarios).

Finally, a limitation of the study was that it did not assess the long-term effects of IES. In fact, it is possible that over a long period of time, modification of the gait parameters might produce fatigue or a change of the gait mechanical efficiency.

CONCLUSIONS

This investigation provides an easy methodological approach for uphill walking without increasing the metabolic demand. Due to its simplicity in use, application and the low cost, it seems suitable for use in both scientific and field/fitness contexts. Considering the high stride variability (stride length/cycle) in the G7IES condition, we suggest using for an easy methodological approach the G2IES condition. Future studies should address the chronic effects of uphill IES training related both to the metabolic demand and gait variability.

Conflict of Interest Declaration

The authors declare that they have no competing interests.

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