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Self-paced and fixed speed treadmill walking yield similar energetics and biomechanics across different speeds

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A R T I C L E I N F O

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A B S T R A C T

Background: Treadmill assessments are often performed at a fixed speed. Feedback-controlled algorithms allow users to adjust the treadmill speed, hereby potentially better resembling natural self-paced locomotion. However, it is currently unknown whether the energetics and biomechanics of self-paced differ from fixed-paced treadmill walking. Such information is important for clinicians and researchers using self-paced locomotion for assessing gait.
Research question: To investigate whether energy cost and biomechanics are different between self-paced and matched-speed fixed-paced locomotion.
Methods: 18 healthy participants (9 males/9 females, mean ± standard deviation age 24.8 ± 3.3 years, height 1.71 ± 0.81 m, weight 65.9 ± 8.1 kg) walked at four different self-paced speeds (comfortable, slow, very slow, fast) in randomized order on an instrumented treadmill while three-dimensional motion capture and gas exchange were measured continuously. The average walking speed during the last 2 min of the self-paced trials was used to match the speed in fixed-paced conditions. Linear mixed models were used to assess differences in mean values and within-subject variations between conditions (self-paced and fixed-paced) and speeds. Statistical Parametric Mapping was used to assess differences in kinematics of the lower limb between conditions.
Results: Although self-paced walking consistently resulted in a 4–6% higher net cost of walking, there were no significant differences in the net cost of walking between conditions. Further, there were also no differences of clinical relevance in spatiotemporal outcomes and sagittal-plane lower-limb kinematics between the self-paced and fixed-paced conditions. Within-trial variability was also not significantly different between conditions.
Significance: Self-paced and fixed-paced treadmill walking yield similar energetics and kinematics in healthy young individuals when mean values or linear measures of variation are of interest.

1. Introduction

Treadmill locomotion is often preferred over overground locomotion in a variety of research and clinical settings. Treadmills allow better control of environmental conditions, they can be used to assess multiple consecutive strides, and require less space [1]. Treadmill locomotion is usually performed at an imposed (fixed) speed set by the user, whereas overground locomotion is performed at a self-paced speed. The fixed speed in treadmill locomotion may reduce the natural variability in locomotion speed as seen in overground locomotion [2]. In addition, it can also reduce the neuromuscular [3] and stride dynamics variability [2,4–8]. As a result, applications of self-paced treadmills have gained interest in both patient and healthy populations purposes, ranging from studies to quantify muscle fatigue during walking in persons with Multiple Sclerosis to $VO2_{max}$ testing during running in healthy athletes [9–12].

Despite the increasing popularity of self-paced treadmill locomotion, only few studies have investigated the effects of self-paced versus matched speed fixed-paced locomotion and most studies found no difference of clinical relevance. Specifically, two studies have compared spatiotemporal parameters, kinematics and kinetics [2,13], one study compared muscle activity [3], and two studies compared dynamic

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stability [14,15] between the two conditions during walking. Indeed, Sloot et. al. [13] found that spatiotemporal, kinetic and kinematic differences between self-paced versus matched speed fixed-paced walking did not exceed the threshold for clinical relevance. In addition, variability of spatiotemporal [2,16], kinetic and kinematic parameters [13] during self-paced walking is reported to be slightly higher compared to fixed-paced walking.

While gait variability is reported to be a strong predictor for the energetic Cost of walking (Cw) [17], no study has compared the energetics and gait variability of self-paced versus fixed-paced treadmill locomotion. Recently, Seethapathi, Srinivasan [18] showed that oscillated walking at a fixed speed increased the Cw compared to walking at a constant fixed speed. Likely, the increased mechanical braking and propulsion forces for redirecting the centre of mass at oscillating speeds explained the higher Cw. However, the magnitude of the oscillating walking speed might not reflect the natural variability typically observed in self-paced treadmill walking.

Therefore, the primary aim of this study was to assess whether the Cw at multiple walking speeds differed between self-paced and matched-speed fixed-paced treadmill walking in healthy adults. A secondary aim was to investigate differences in spatiotemporal and lower-limb sagittal-plane kinematic outcomes. Finally, since variability is reported to be higher during self-paced treadmill walking in spatiotemporal [2,16], and kinematic [13] patterns when compared to fixed-paced walking, it is expected that the Cw also shows higher variability. A tertiary aim is therefore to investigate differences in the variability of the energetic cost and spatiotemporal parameters of walking between self-paced and matched-speed fixed-paced treadmill walking.

2. Methods

18 healthy participants (mean ± standard deviation (SD) age, body height, leg length and mass of 24.8 ± 3.3 years, 171.2 ± 8.2 cm, 84.5 ± 5.2 cm, and 65.9 ± 8.1 kg) that were free of any musculoskeletal injuries volunteered to participate in the study. The study was approved by the local ethics committee (nr. 2019–1128), conducted in compliance with the declaration of Helsinki and all participants signed informed consent form prior to the measurements. Individuals that were comfortable with treadmill walking, aged 18–35 years, had a body mass index (BMI) of $<$ 30, free of injuries or diseases that could affect gait and could walk continuously for a minimum of 40 min were recruited. The study protocol was registered at the Dutch trial register under number NL8160.

2.1. Experimental set-up

A detailed experimental set-up is provided in Supplementary File 1. All participants completed a single test session and were instructed to avoid strenuous activity 24 h, and eating and drinking (with exception of water) up to 3 h before the session to ensure metabolic resting state. When entering the lab, height was measured using a stadiometer (SECA, model 213, Hamburg, Germany). Participants were then instructed to lay down in a comfortable supine position for 35 min while measuring resting metabolic rate (RMR) using a ventilated hood that was connected to the indirect calorimeter (Omnical, Maastricht Instruments, Maastricht The Netherlands) [19]. A calm nature documentary was shown during the measurement and participants were instructed not to fall asleep. After the measurement of resting metabolism, 26 retroreflective skin markers were attached using a modified lower-limb and trunk marker set (Human Body Model v2) and body mass was measured by the force platforms during the subject calibration van den Bogert et al. [20].

The computer assisted rehabilitation environment (CAREN, Motek, The Netherlands) system combines an instrumented split-belt treadmill (ForceLink, Culemborg, The Netherlands) with a 12-camera three-dimensional motion capture system (VICON NEXUS v2.7, Oxford Metrics Group, Oxford, UK) and was used to measure kinematic outcomes during walking (Supplementary File 1). During walking the participants wore a face mask and respiratory gasses were captured using an indirect calorimeter [19].

2.2. Protocol

Participants were instructed to walk for six minutes at a self-paced comfortable speed serving as familiarization with treadmill walking [21,22] and wearing of the face mask. The average walking speed during the following two minutes was determined as the comfortable walking speed and used to set the target speed ranges for the other self-paced conditions. Subjects were instructed to walk 20% faster and 20% and 40% slower than comfortable to reflect a variation in speeds that may be encountered in real-life conditions referred to as “comfortable”, “fast”, “slow” and “very slow”. Participants were provided with real-time feedback about their walking speed using the virtual environment and instructed to find a comfortable pace within a ± 5% range of the calculated speed. For details about the self-paced algorithm used we refer to [13,23] and Supplementary File 1.

All conditions were performed for 4 min, with data collection being started in the last 2 min to ensure a steady-state metabolism and washout of former speeds. The average walking speed of the self-paced trials was used to match the speeds in fixed-paced conditions. All self-paced conditions after the comfortable speed were performed in a randomized order as determined by block randomization by 4 blocks of 3 conditions with the fixed-paced conditions being performed in the same order as the self-paced conditions.

2.3. Data analysis

2.3.1. Energy expenditure

Resting Metabolic Rate (J•24 h) was computed from the average O_2 and CO_2 measured during the last 5 min of the 35 min RMR measurement [24] using Weir’s non-protein equation. The energy consumption of walking ($J{\bullet}min^{-1}$) at each speed was computed from the average O_2 and CO_2 measured during the last 2 min of each condition. RMR ($J{\bullet}min^{-1}$) and subtracted from the energy consumption of walking to determine net walking energy consumption expressed as $J{\bullet}kg^{0.67}{\bullet}m^{-1}$[25].

2.3.2. Spatiotemporal and kinematic data

The average horizontal speed of the foot during ground contact determined by the ankle markers was used to represent walking speed. Spatiotemporal variables of interest were cadence, step length, step width, step time, and double support time. Average values were calculated per step for the left and right leg. The definitions of all spatiotemporal parameters are reported in Supplementary File 1. Lower limb sagittal plane joint kinematics for the hip, knee and ankle were calculated in real-time using the Human Body model V2 (HBM; Motek Medical BV).

Kinematic data was normalised to 100% gait cycle defined as two consequent ipsilateral initial contact on a single belt as described by Zeni et al. [26]. Both vertical ground reaction forces and marker data were combined for an accurate determination of initial contact.

2.3.3. Statistics

All statistical analyses were performed using SPSS Version 25 (IBM Corporation, Chicago, IL), unless stated otherwise. Means ± SD, were reported for all analyses. Normality was checked using Q-Q plots and Shapiro Wilk’s test. Main and interaction effects of condition and walking speed on the Cw and spatiotemporal parameters were assess by using Linear Mixed Models. Both walking condition and speed were set as fixed effects. Subjects were included as random effect using the variance components covariance- structure and each subject was considered to have a different intercept. The model’s best fit included a Restricted Maximum Likelihood. The magnitude of within subject variability in spatiotemporal outcomes was reported as coefficient of variation and expressed as percentage ([SD / mean] x 100).

Differences in sagittal-plane joint kinematics of the right leg were assessed using statistical-parameter mapping (SPM), using open-source SPM1d code (vM.0.4.5, www.spm1D.org). This method assesses differences between data points in consequent time series, rather than discrete values only. Normal distribution was assessed with the repeated measures ANOVA normality check. Consequently, a repeated measures ANOVA was performed which computed a Statistical Parametric Map for the conventional univariate F or t- at every time point, defined as 100 iterations resembling one gait cycle [27]. Bonferroni correction was performed to account for multiple conditions, resulting in a critical threshold of $\alpha < 0.0125$, reflecting not more than 1.25% exceeding the equally smooth random data. In case this threshold was exceeded, a main effect was considered significant. Additional SPM tests were performed for further assessing whether significant outcomes were attributed to differences in magnitude or time-shift [28]. Differences attributed to the magnitude were assessed by performing a paired T-tests between conditions at the specific regions which showed significant differences. Differences due to time-shift were assessed by normalising the data to peak flexion angles. A critical threshold of $\alpha < 0.05$ was considered significant.

3. Results

3.1. Walking speed

Mean ± SD walking speed for each speed per condition is reported in Table 1. Linear mixed models analysis revealed that walking speed was not different between self-paced and fixed-paced treadmill walking (F=.559, p = .456). As expected, there was however a significant difference in walking speed between speeds (F=2544, $p < .0001$). The variability in walking speed is presented in Table 2 and differed between conditions, speeds and showed an interaction between condition and speed (F=358, $p < .0001$; F=6.54, $p < .0001$; F=6.92, $p < .0001$, respectively). Pairwise comparison showed a significantly higher variability when walking at comfortable compared to fast speed. All data generated with this study is freely available as a Supplementary File (DOI:10.17605/OSF.IO/AENRW).

3.2. Energy expenditure

Mean ± SD RMR was 0.12 ± 0.02 MJ•kg•day^{-1} (261.5 ± 48.7 ml O2•min^{-1}). There was no difference in the overall mean Cw between self-paced and fixed-paced treadmill walking (F=3.920, $p = .050$). However, the net Cw differed between walking speeds (F=4.345, $p = .006$) but without an interaction effect of condition * speed (F=0.040, $p = .989$). Pairwise comparisons showed a significantly higher net Cw during very slow and fast walking when compared to comfortable walking in both self-paced and fixed-paced conditions. There were no significant differences in the net Cw between the other speeds. The individual net Cw per speed in both conditions is presented in Fig. 1. There was no significant main effect of walking condition, speed condition and no significant condition * speed effect on the variability of Cw (F=2.13, $p < .147$; F=2.42, $p = .070$; F=1.997, $p = .118$, respectively, Table 2).

3.3. Spatiotemporal

More detailed statistical outcomes on spatiotemporal and kinematic parameters are reported in Supplementary File 1. The mean ± SD number of steps at all speeds used for analysis of spatiotemporal parameters was 108 ± 11 and 112 ± 15, for fixed and self-paced walking, respectively. Overall, there were generally no significant differences in the mean or the variability of spatiotemporal parameters between the self-paced and fixed-paced conditions. When significant differences were observed between self-paced and fixed-paced conditions, the magnitude of the difference was very small. Specifically, the only mean spatiotemporal parameter that differed between the self-paced and fixed speed conditions was step length which was − 0.005 m shorter in self-paced conditions. The variability of step length was 1.1% smaller and step width 0.9% smaller in fixed-paced walking. The parameters that differed between speeds were step length, cadence and double support time. Furthermore, the variability of step length, cadence, step time and double support time differed between speeds. No significant interaction effects of condition*speed were found.

3.4. Kinematics

Overall, there were generally no significant differences in the mean kinematic parameters between the self-paced and fixed-paced conditions (Supplementary Figure 1). When significant differences were observed between self-paced and fixed-paced conditions, the magnitude of the difference was very small. SPM analysis showed a significantly larger hip extension angle during fixed-paced very slow walking between 51% and 61% of the gait cycle with a mean difference of − 0.7 degrees Fig. 2. The knee flexion angle was larger during slow fixed speed walking with a mean difference of 0.8 degrees between 69% and 72% of the gait cycle. At fast speed, the knee flexion angle was 0.8 degrees greater in self-paced walking between 81% and 87% of the gait cycle. No other significant differences were found between conditions. Additional SPM analysis showed that the difference in knee angle at slow and fast speeds were attributable to a difference in magnitude between both conditions without an effect of time-shift.

4. Discussion

The primary aim of this study was to compare the energy cost between self-paced and matched speed fixed-paced treadmill walking. It was expected that self-paced treadmill walking resulted in a lower Cw due to the higher natural variability as seen in daily life locomotion. Our findings show no significant differences in energy cost between self-paced and fixed-paced treadmill walking, regardless of the walking speed. Further, there were few significant differences in mean spatiotemporal outcomes, and sagittal-plane lower-limb kinematics between

Table 1
Mean ± SD energy cost and spatiotemporal parameters for both conditions per speed.

	very slow		slow		comfortable		fast	
	self-paced	fixed	self-paced	fixed	self-paced	fixed	self-paced	fixed
Walking speed (m•s^{-1})^{b}	0.83 ± 0.1	0.83 ± 0.11	1.04 ± 0.12	1.04 ± 0.12	1.28 ± 0.14	1.29 ± 0.15	1.52 ± 0.15	1.53 ± 0.18
Net Cw (J•kg$^{0.67}$•m^{-1})	3.58 ± 0.74	3.42 ± 0.85	3.29 ± 0.56	3.09 ± 0.45	3.28 ± 0.54	3.16 ± 0.64	3.62 ± 0.84	3.42 ± 0.65
Mean spatiotemporal								
Step length (m)^{ab}	0.53 ± 0.04	0.54 ± 0.04	0.6 ± 0.04	0.6 ± 0.04	0.67 ± 0.05	0.67 ± 0.05	0.73 ± 0.05	0.74 ± 0.05
Step width (m)	0.17 ± 0.04	0.17 ± 0.04	0.17 ± 0.04	0.16 ± 0.04	0.16 ± 0.03	0.17 ± 0.04	0.17 ± 0.04	0.17 ± 0.04
Cadence (steps•min^{-1})^{b}	94 ± 7	93 ± 8	105 ± 8	104 ± 8	115 ± 7	115 ± 7	124 ± 8	124 ± 8
Double support time (s)^{b}	0.15 ± 0.03	0.16 ± 0.03	0.12 ± 0.02	0.12 ± 0.02	0.1 ± 0.02	0.1 ± 0.02	0.09 ± 0.01	0.09 ± 0.01

a=significant difference between condition, ^{b}= significant differences between speeds with p = <.05

Table 2
Mean within subject CV ± SD in percentages for all spatiotemporal parameters and energy cost for both conditions per speed.

	very slow		slow		comfortable		fast	
	self-paced	fixed	self-paced	fixed	self-paced	fixed	self-paced	fixed
Walking speed (%)^{ab}	5.2 ± 2.1	0 ± 0	4.2 ± 2.2	0 ± 0	4.4 ± 2.4	0 ± 0	2.6 ± 1	0 ± 0.1
Net Cw (%)	8.3 ± 0.04	8.3 ± 0.03	7.5 ± 0.02	8.1 ± 0.04	10.8 ± 0.06	7.6 ± 0.03	7.5 ± 0.05	6.6 ± 0.03
Mean spatiotemporal								
Step length (%)^{ab}	5.2 ± 2	3.9 ± 1.9	4.1 ± 1.9	2.5 ± 0.9	3.2 ± 1.5	2 ± 0.7	2.3 ± 0.9	1.9 ± 0.9
Step width (%)^{a}	12.4 ± 4.8	13.5 ± 4.1	12.8 ± 3	13.9 ± 2.9	12.9 ± 2.4	14.2 ± 3.3	14.2 ± 3.8	14.4 ± 3.1
Cadence (%)^{b}	3.8 ± 1.4	3.7 ± 1.4	3.4 ± 1.3	2.8 ± 0.8	2.4 ± 0.9	2.3 ± 0.9	2.2 ± 0.6	2.2 ± 0.8
Double support time(%)^{b}	12 ± 2.7	11.6 ± 4.2	11.1 ± 2.9	9.5 ± 2.2	10.7 ± 2.8	10.6 ± 2.8	11.7 ± 2.2	11.8 ± 2.1

a=significant difference between condition, b= significant differences between speeds with $p = <.05$

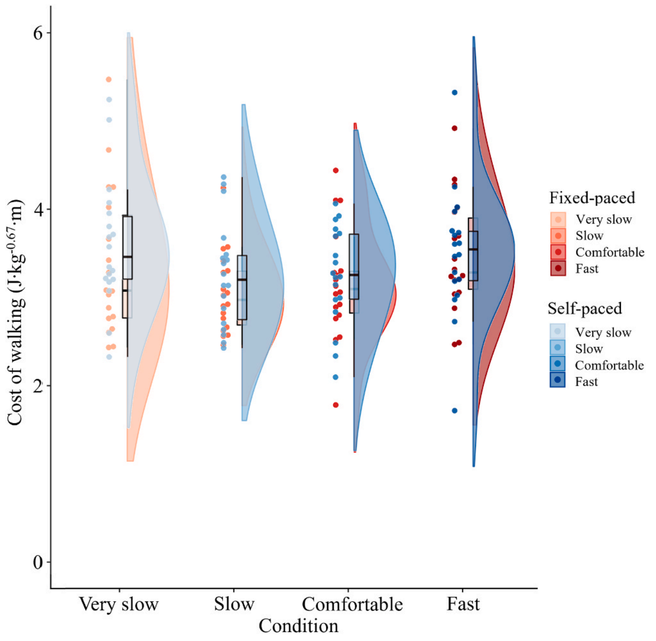

Fig. 1. Raincloud plot of the net Cost of walking at all speeds in both conditions. Dots represent individual data points. Box and whiskers represent the median and interquartile range.

self-paced and fixed-paced conditions. When significant differences were observed between conditions, the magnitude was below the clinical relevance. Similarly, the variability in Cw and most biomechanical outcomes were not different between conditions.

Self-paced walking showed a higher variability in walking speed compared to fixed-paced walking, with an overall mean coefficient of variation of 4.07%. A previous study showed that treadmill walking at an oscillating fixed speed increased the Cw compared to walking at a constant fixed speed [18]. In contrast, our study did not show significant differences between fixed-paced and self-paced Cw, regardless of walking speed. This is likely because the oscillations in speed within each self-paced condition were relatively small in our study (overall SD of 0.04 $m \cdot s^{-1}$), while the fixed oscillating speed variability used by Seethapathi, Srinivasan [18] was much larger (0.13–0.27 $m \cdot s^{-1}$), possibly resulting in higher propulsive and braking requirements, hence higher energy consumption. The difference in the Cw between self-paced and fixed-paced walking was in line with the standard error of measurement reported previously, with the mean overall variability in our study being 7.72% when expressed as $VO_2 \cdot min^{-1}$ vs a CV of 5.2–7.6% $VO_2 \cdot min^{-1}$ for walking at 0.89–1.78 $m \cdot s^{-1}$ [29]. Similarly, the previous reported minimum detectable change of 6.9–9.6% for gross $VO_2 \cdot kg \cdot min^{-1}$ [30] is in line with our variability, expressed as coefficient of variation, for the overall difference between self-paced and fixed-paced walking.

Collectively, these findings therefore indicate that the differences between self-paced and fixed-paced walking energetics are likely not practically or clinically relevant. While Cw did not differ between self-paced and fixed-paced conditions, the Cw was higher at slower and faster speeds relative to the comfortable speed. This finding is in line

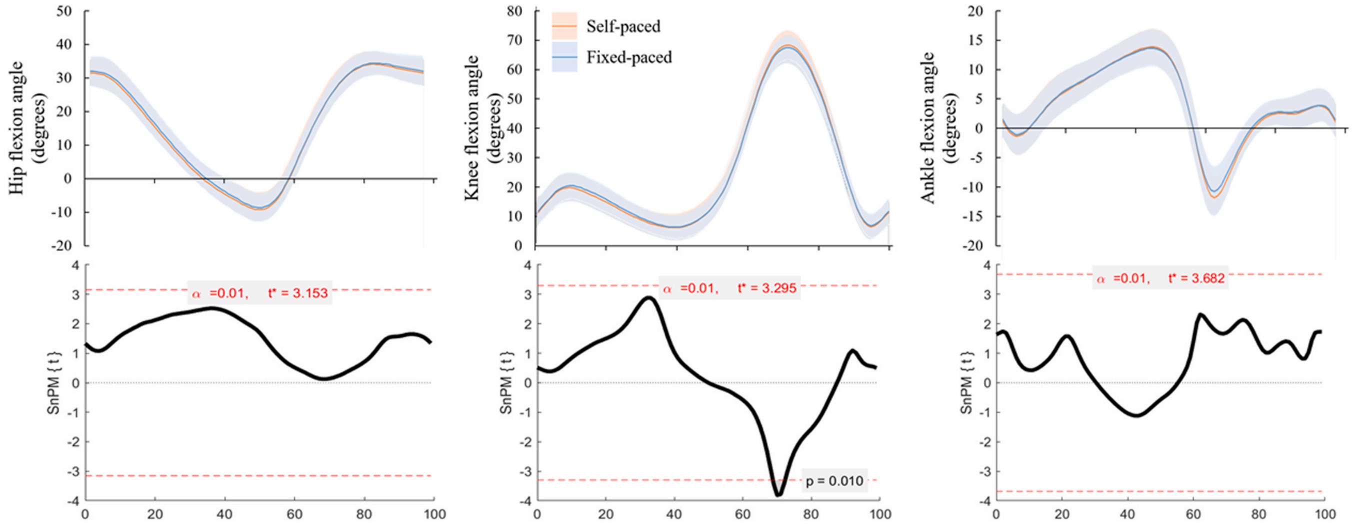

Fig. 2. Kinematics and statistical parametric mapping outcomes for the hip, knee and ankle angle in sagittal plane, normalised to 100% of the gait cycle for walking at slow speed. The solid line reflects the mean sagittal-plane joint angle for fixed paced (blue) and self-paced walking (orange), with the shaded area reflecting the standard deviation.

with previous studies that report an U-shaped relation between the Cw and walking speed [31]. The increased Cw at these speeds relative to the self-selected comfortable speed may be due to less efficient muscle-tendon functioning associated with alterations in walking biomechanics [32].

The findings of our study are in line with other studies that show that spatiotemporal and kinematic differences between self-paced versus matched speed fixed-paced walking do not exceed the threshold for clinical relevance [2,13]. Interestingly, SPM showed a small significant difference in sagittal-plane hip angle between the very slow self-paced and fixed-paced conditions. Similarly, for knee flexion the magnitude of this difference was very small ranging from − 0.73 – 0.84 degrees, which is smaller than the standard error of measurement previously reported for this angle [33,34], and below the threshold considered to be clinically relevant [33]. These findings therefore collectively suggest that self-paced and fixed-paced walking exhibit largely similar biomechanics.

Although we found no substantial differences in mean outcomes, self-paced walking was characterized by higher (within-trial) variability in walking speed (i.e., higher fluctuations during a walking trial). The overall variability of energy cost was however not significantly different, with an overall mean difference of 0.85%. Similarly, the variability of spatiotemporal outcomes was either not significantly different between conditions or the magnitude of the difference was trivial (Table 2). The similar variability in most outcomes during self-paced treadmill walking are in contrast to the findings of other studies that reported higher variability in self-paced walking when compared to fixed-paced walking [2,13,16]. For example, Sloot et al. [13] observed higher variability in the long-term component of walking speed variability. Similarly, Choi et al. [16] showed higher variability in fractal dynamics of spatiotemporal outcomes. Most of these studies however used non-linear measures of variability, whereas we used the (linear) coefficient of variation. Yet, Wiens et al. [2] also determined the variation and showed higher coefficients of variation for step time, step length and step speed in self-paced treadmill walking when compared to fixed-paced walking. The conflicting findings with our study may be due to learning effects in the study by Wiens et al. [2] which can be explained by the decrease in variation in the second session compared to the first. Overall, since there are no substantial differences in mean self-paced and fixed-paced treadmill walking energetics and biomechanics, these findings suggest self-paced walking may be used interchangeably with fixed-paced walking in healthy young individuals. However, self-paced walking may better represent the natural movement variability most [2,4–8,16], but not all outcomes [3] and therefore be more suited to study variability in controlled conditions.

5. Limitations

Several limitations to this study should be considered when interpreting the findings. First, the algorithm used for adjusting the treadmill speed in self-paced conditions may affect variability of self-paced conditions and care should therefore be taken when generalizing these findings to settings in which a different self-paced algorithm or experimental set-up from the current is used [2,23,35–37]. Similarly, the presence of visual optic flow of the 180 degrees cylindrical screen of the CAREN system may also affect walking speed and thus walking biomechanics and energetics [38]. Further, we used a fixed order in which the self-paced condition always preceded the fixed-paced condition. While this may have introduced order effects, this fixed sequence was required to ensure we could match the walking speed in both conditions. Additionally, since we found no substantial differences between the two modes any order effect is likely negligible.

6. Conclusion

Overall, since we found no substantial differences, it can be concluded that self-paced and fixed-paced treadmill walking yield similar energetics and kinematics when mean values or linear measures of variation are of interest.

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Author contributions

Kyra Theunissen and Bas van Hooren: Data collection. Kenneth Meijer and Guy Plasqui: supervision. All authors contributed to the conceptualization, methodology, formal analysis, writing - review & editing the manuscript and approved the final version prior to submission.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2021.11.005.

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