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A comparison of variability in spatiotemporal gait parameters between treadmill and overground walking conditions

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ABSTRACT

Motorized treadmills are commonly used in biomechanical and clinical studies of human walking. Whether treadmill walking induces identical motor responses to overground walking, however, is equivocal. The purpose of this study was to examine differences in the spatiotemporal gait parameters of the lower extremities and trunk during treadmill and overground walking using comparison of mean and variability values. Twenty healthy participants (age 23.8 ± 1.2 years) walked for 6 min on a treadmill and overground while wearing APDM 6 Opal inertial monitors. Stride length, stride time, stride velocity, cadence, stance phase percentage, and peak sagittal and frontal plane trunk velocities were measured. Mean values were calculated for each parameter as well as estimates of short- ($SD1$) and long-term variability ($SD2$) using Poincaré analyses. The mean, $SD1$, and $SD2$ values were compared between overground and treadmill walking conditions with paired t-tests ($\alpha = 0.05$) and with effect size estimates using Cohen's d statistic. Mean values for each of the gait parameters were statistically equivalent between treadmill and overground walking ($p > 0.05$). The $SD1$ and $SD2$ values representing short- and long-term variability were considerably reduced ($p < 0.05$) on the treadmill as compared to overground walking. This demonstrates the importance of consideration of gait variability when using treadmills for research or clinical purposes. Treadmill training may induce invariant gait patterns, posing difficulty in translating locomotor skills gained on a treadmill to overground walking conditions.

1. Introduction

The use of motorized treadmills is common in both research and clinical settings. Compared with overground walking, the compact nature of a treadmill has advantages of decreased space requirements, ease of observing repeated strides and controllability of walking speed. However, if motor responses differ between treadmill and overground walking, the transferability of training from treadmill to overground walking may be impacted. Several studies comparing gait parameters between treadmill and overground walking have reported equivocal findings [1–6]. Riley et al. [5], for example, reported that spatiotemporal gait parameters such as cadence, stride length, stride time and single and double support time were very similar in treadmill and overground walking and concluded that walking on a treadmill produced no discernable difference in the timing of gait cycle events. In contrast, others have reported that individuals walk with shorter strides and increased cadences on a treadmill [1,4]. While the research regarding spatiotemporal gait parameters is quite extensive—though conflicting—research regarding differences in the variability of these gait parameters during treadmill and overground walking is less readily available. Assessing stride-to-stride variability in spatiotemporal gait parameters, such as in step width, stride time, and swing time, has been shown to potentially be more sensitive to change than measures of gait based on average stride patterns [7].

In the limited studies comparing the variability of spatiotemporal gait parameters in healthy participants for treadmill and overground walking, treadmill walking may be associated with reduced variability in stride time and trunk accelerations [8,9]. However, additional spatiotemporal gait parameters are in need of investigation. In studies examining gait variability,

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classical linear measures of variability (e.g. comparing standard deviations (SDs) and coefficients of variation) are often used [10]. Nonlinear Poincaré analyses may offer a more descriptive method for assessing variability; Poincaré analyses produce plots of consecutive data points that can be used to quantify measures of short- and long-term variability. Poincaré analyses have been used in cardiovascular research to quantify heart rate variability [11] and their application as a measure of gait variability is emerging [12]. No study, to our knowledge, has compared gait variability in overground and treadmill walking via Poincaré analyses.

Several studies comparing rehabilitation outcomes for patients undergoing treadmill training versus overground training have reported differences between the two training modalities [13–16]. For example, Combs-Miller et al. [14] reported that when participants with chronic stroke were matched for task and dose of walking interventions, an overground walking training group demonstrated significantly greater improvements in walking speed, gait symmetry and activity than a treadmill training group. Discrepancies in rehabilitation outcomes occurring with treadmill versus overground training emphasize potential differences in the two walking modalities. Since those discrepancies are present, understanding how treadmill ambulation differs from overground ambulation is important. The purpose of this study was to examine multiple spatiotemporal gait parameters during treadmill and overground walking by comparing traditional mean values of the measurements as well as variability of those same measurements via nonlinear Poincaré analyses. We hypothesized that when individuals ambulate on a treadmill, they would demonstrate comparable mean values but reduced variability when compared with overground walking.

2. Methods

2.1. Participants

Twenty healthy volunteers (9 males, 11 females) participated in this study. A convenience sampling method was used. Participant characteristics are shown in Table 1. For inclusion, participants were required to have previous experience with treadmill walking and be able to complete two consecutive 6 min walks. Individuals reporting any abnormalities (e.g. due to orthopedic injury, lower limb pain, or neurological injury) that may impact gait or balance were excluded from participation. All participants gave written informed consent prior to beginning the trials. The experimental protocol was approved by the local Institutional Review Board.

2.2. Instrumentation

Gait parameters during treadmill and overground walking were measured using the APDM Movement Monitoring inertial sensor system (APDM Inc., Portland, OR). The 22 g sensors include triaxial accelerometers, gyroscopes, and magnetometers. A six sensor configuration was used, consisting of two ankle, two wrist, one sternal, and one waist sensor. Signals were sampled at 1280 Hz with 14 bit resolution, and the data streamed wirelessly to a computer. Data were automatically analyzed with the corresponding Mobility Lab^{TM} software package. The IWalk plugin for Mobility Lab^{TM} was chosen due to its ability to measure gait parameters during the full 6 min of testing.

Table 1
Participant descriptive characteristics.

	Mean	SD	Minimum	Maximum
Age (years)	23.8	1.2	22	27
Body mass (kg)	72.2	15.0	49.9	96.6
Body height (m)	1.74	0.10	1.54	1.90
Overground velocity (m/s)	1.57	0.15	1.24	1.80

SD: standard deviation. Overground velocity was determined by mean of three repetitions of the 10 m walk test.

2.3. Procedure

Subjects were asked to wear comfortable walking shoes and clothes suitable for completing light exercise. Upon arrival, each participant signed an informed consent form. Each participant then self-reported age and height; body weight was measured via a Healthometer scale. The order of the walking trials (i.e. treadmill first or overground first) was randomized. Self-selected walking speed was calculated for each participant using a 10 m walk test (10MWT). For the 10MWT, each participant was instructed to walk at his/her normal, comfortable walking speed across a 14 m walkway. Time taken to complete the middle 10 m of the walkway was recorded via stopwatch. Three trials were completed and times averaged across the trials to calculate self-selected walking speed. During the treadmill trial, the treadmill speed was set at each participant's self-selected walking speed. The treadmill used in this study was a standard motorized treadmill (Quinton Medtrak Cr60).

After determining self-selected walking speed, each participant was fitted with the six inertial sensors. The inertial sensors were reconfigured prior to application for each participant. The sensors were placed thusly: bilateral ankles (lateral to the tendon of the tibialis anterior); low back (L4–L5 region); sternum; bilateral wrists (dorsal surface). The sensors were secured snugly via elastic straps. For both the treadmill and overground trials, participants were given the instructions: "Do not start moving until I say go; once you start, continue walking until I say stop." No encouragement or additional verbal instructions were given during trials. The participant was notified at the halfway point and when 1 min remained during each trial. A 3 min seated rest break was permitted between trials.

For the overground trial, each participant walked along a 42 m path within a hallway in a hospital rehabilitation unit. This path length was determined to be the longest range the inertial sensors could record without substantial lag time. Each participant walked back and forth at a comfortable pace for 6 min.

For the treadmill trial, participants walked on a treadmill set at each subject's preferred walking speed, as determined by the 10MWT. Once the treadmill reached the preferred walking speed, data collection began. At the completion of 6 min, data collection was halted and the researcher stopped the treadmill.

2.4. Data processing

Signal processing and calculation of gait parameters were performed via the automatic analysis algorithms of the Mobility Lab^{TM} system's IWalk plugin. Turns during the overground walking condition were detected with gyroscopes in the trunk and lumbar sensors with a mathematical model described by Salarian et al. [17] and data from gait cycles during turns were filtered out of the analysis. Additionally, since we desired to analyze steady-state ambulation during both overground and treadmill walking conditions, data from gait cycles in which participants decelerated into turning cycles or accelerated from turning cycles were also filtered out of the analysis by identifying measures that departed by three or more standard deviations from mean values during steady state ambulation.

Of the many parameters analyzed in the IWalk plugin, we opted to include seven specific gait parameters for further analysis: stride time and cadence measures were used as markers of temporal

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rhythm; stride length and stride velocity measures were used as markers of spatial and spatiotemporal pacing; the percentage of the gait cycle spent in the stance phase of gait was used as a marker of gait cycle phases; peak sagittal and frontal plane trunk velocities were used as markers of trunk control. Operational definitions for the investigated gait parameters are provided in Table 2.

2.5. Data analysis

Descriptive statistics (means and SDs) were calculated for each parameter measured traditionally as the average value over all strides in the trial series, as well as for the estimates of short- and long-term variability from the Poincaré analyses. In a Poincaré plot, results of one measurement in trial series data are plotted as a function of the immediately preceding measurement. For data denoted by $x_0, x_1, x_2, x_3 \ldots$, the return map plots the points (x_0, x_1), (x_1, x_2), (x_2, x_3), …, and the scatter plot permits one to visualize variability of the trial series for x_n points (Fig. 1). Standard descriptors for quantifying Poincaré plot geometry are obtained by fitting an ellipse to data defined by the standard deviations (*SD*) along the minor and major axes of the ellipse [11,12]. *SD*1 is defined by the *SD* of the distances of points from the major axis and represents short-term variability in trial series data and *SD*2 is defined by the *SD* of the distance of points from the minor axis and represents long-term variability in trial series data [12]. The descriptors *SD*1 and *SD*2 are calculated as:

$$SD1 = \frac{\sqrt{2}}{2} SD(x_n - x_{n+1})$$

and

$$SD2 = \sqrt{2SD(x_n)^2 - \frac{1}{2} SD(x_n - x_{n+1})^2}$$

Table 2
Operational definitions of investigated gait parameters.

Gait parameter	Operational definition
Stride length (m)	Distance between two consecutive right foot falls at the moments of initial contact
Stride time (s)	Duration of a complete gait cycle
Stride velocity (m/s)	Stride length divided by stride time
Cadence (steps/min)	Stepping rate
Stance (% gait cycle)	Percentage of gait cycle that right foot is on the ground
Peak sagittal plane trunk velocity (°/s)	Peak angular velocity of trunk in sagittal plane
Peak horizontal plane trunk velocity (°/s)	Peak angular velocity of trunk in horizontal plane

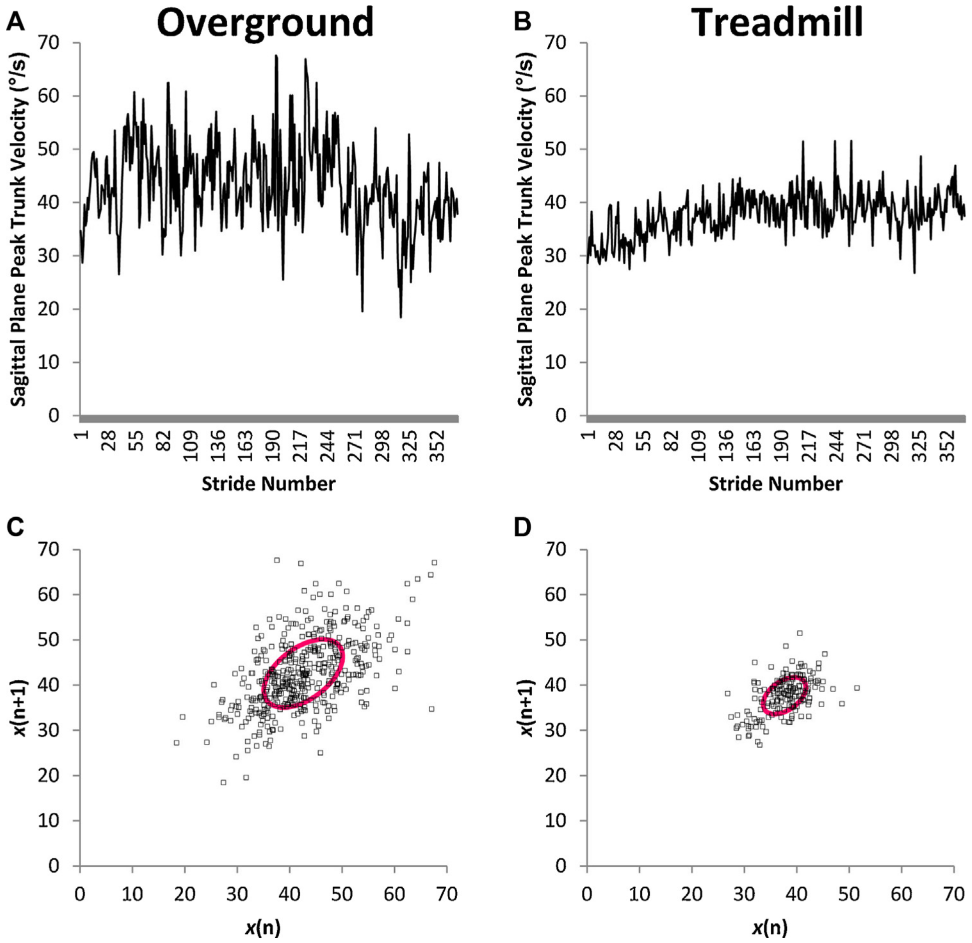

Fig. 1. Representative example of trial series data (A and B) and Poincaré plots (C and D) for the peak sagittal plane trunk velocity gait parameter from a single participant. Figures on the left (A and C) illustrate peak sagittal plane trunk velocities from every stride during overground walking; figures on the right (B and D) illustrate peak sagittal plane trunk velocities from every stride during treadmill walking. The Poincaré plots (C and D) represent data from each individual stride during a trial, $x(n)$, on the x-axis, and the subsequent stride, $x(n+1)$, on the y-axis. The ellipses represent magnitudes of the standard deviations of the distances of paired-data points from the major axis (short-term variability) and of the distances of paired-data points from the minor axis (long-term variability) of the ellipses.

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Mean values of the traditionally measured gait parameters and of the *SD*1 and *SD*2 measurements were compared between overground and treadmill walking conditions with paired *t*-tests ($\alpha = 0.05$) and with effect size estimates using Cohen's *d* statistic. Descriptive data and the paired *t*-tests were calculated with IBM SPSS 21.0 software (IBM Corp, Armonk, NY).

3. Results

All participants successfully completed the testing protocol. Data provided in Table 3 indicate that traditional mean values of the stride length, stride time, stride velocity, cadence, stance phase percentage, and peak sagittal and frontal plane trunk velocity measurements did not differ significantly between the overground and treadmill walking conditions (*p*-values for all comparisons >0.05). In contrast, the short-term variability (*SD*1) and long-term variability (*SD*2) indicators in the gait parameters were reduced significantly for all gait parameters on the treadmill as compared to overground walking (*p*-values for all comparisons <0.05). The effect sizes of comparisons between the short- and long-term variability measurements were considerably greater than the effect sizes for comparisons of the traditional mean measurements (Fig. 2).

4. Discussion

We conducted this study to examine if healthy participants ambulated differently on a treadmill than overground. More specifically, we hypothesized that traditionally measured mean values of multiple spatiotemporal gait parameters would be equivalent between overground and treadmill walking, but that comparing stride to stride variability across the two walking conditions would lead us to conclude that the walking on a treadmill alters the way in which people ambulate. The data supported our hypothesis. Whereas comparing traditional mean values across seven spatiotemporal gait parameters yielded no statistically significant differences between the overground and treadmill walking conditions, comparing short- and long-term variability indicators via Poincaré analyses leads us to conclude that walking on a treadmill induces less variant gait characteristics than walking overground. These findings highlight the importance of considering variability when conducting research or clinical interventions on a treadmill.

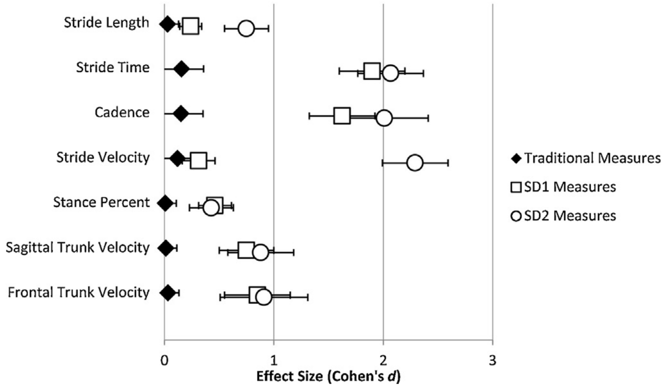

Fig. 2. Effect sizes (Cohen's *d*) of the difference in gait parameters between overground and treadmill walking conditions. *SD*1 represents short-term variability and *SD*2 represents long-term variability indicators in the gait parameters from the Poincaré analyses. Error bars represent 95% confidence intervals of the effect size estimates.

When humans walk, their gait must be sufficiently adaptable to accommodate changing environmental demands yet sufficiently rhythmic, symmetric and stable to prevent falling. Achieving that balance is not inconsequential and implies that a certain magnitude of variability in the gait pattern may represent a healthy state. Indeed, there is evidence that a loss of variability in many physiological systems denotes pathological states of being [18]. Placed in context, if one trains under conditions that limit

Table 3
Comparison of traditional, short-term variability (*SD*1) and long-term variability (*SD*2) measurements for gait parameters during the overground and treadmill walking conditions (mean ± SD).

Gait parameter	Overground	Treadmill	95% CI of the difference	*p*
Stride length (m)				
Traditional measurements	1.57 ± 0.09	1.58 ± 0.09	−0.014 to 0.009	0.675
*SD*1 measurements	0.031 ± 0.012	0.028 ± 0.011	0.001–0.005	0.047
*SD*2 measurements	0.034 ± 0.009	0.028 ± 0.007	0.003–0.009	0.001
Stride time (s)				
Traditional measurements	1.03 ± 0.05	1.03 ± 0.05	−0.006 to 0.021	0.260
*SD*1 measurements	0.012 ± 0.002	0.009 ± 0.002	0.003–0.004	0.001
*SD*2 measurements	0.022 ± 0.005	0.013 ± 0.003	0.006–0.011	0.001
Stride velocity (m/s)				
Traditional measurements	1.53 ± 0.10	1.54 ± 0.09	-0.030 to 0.008	0.232
*SD*1 measurements	0.032 ± 0.011	0.029 ± 0.010	0.001–0.006	0.033
*SD*2 measurements	0.045 ± 0.010	0.027 ± 0.006	0.014–0.022	0.001
Cadence (steps/min)				
Traditional measurements	116.4 ± 5.6	117.3 ± 5.4	-2.3 to 0.6	0.246
*SD*1 measurements	1.378 ± 0.258	0.938 ± 0.283	0.294–0.586	0.001
*SD*2 measurements	2.474 ± 0.584	1.505 ± 0.352	0.686–1.252	0.001
Stance (% gait cycle)				
Traditional measurements	60.0 ± 1.8	59.9 ± 2.0	-0.3 to 0.4	0.916
*SD*1 measurements	1.305 ± 0.651	1.025 ± 0.560	0.126–0.436	0.001
*SD*2 measurements	1.678 ± 0.890	1.319 ± 0.803	0.085–0.633	0.013
Sagittal plane trunk velocity (°/s)				
Traditional measurements	38.6 ± 10.5	38.4 ± 11.8	-2.0 to 2.3	0.881
*SD*1 measurements	4.929 ± 1.696	3.786 ± 1.331	0.784–1.503	0.001
*SD*2 measurements	6.196 ± 2.061	4.617 ± 1.484	0.986–2.172	0.001
Frontal plane trunk velocity (°/s)				
Traditional measurements	44.2 ± 11.2	43.9 ± 11.7	-1.7 to 2.5	0.715
*SD*1 measurements	7.052 ± 2.232	5.400 ± 1.604	1.062–2.242	0.001
*SD*2 measurements	8.613 ± 2.615	6.450 ± 2.118	1.327–2.999	0.001

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variability, the training modality may impede motor performance. More specifically, translating walking function from a treadmill to overground conditions may be limited secondary to contextual differences between the two modalities that alter natural variability in the motor system. As an example, Combs-Miller et al. [14] attributed those differences as an explanation for why persons with chronic stroke who participated in 2 weeks of overground gait training demonstrated greater improvements in walking speed and gait symmetry than those who participated in 2 weeks of treadmill training. As another example in which variability in the training modality may influence motor performance, Reisman et al. [19] provided evidence that locomotor adaptation following treadmill training may be more effective when that training occurs on a split-belt treadmill in which users must accommodate their interlimb coordination to belts moving at different speeds and with contextually different demands. While our study was not designed to test a hypothesis that treadmill training may have limited clinical utility, our findings do indicate that healthy persons walk with more invariant gait patterns on a treadmill than overground.

Differences between overground and treadmill walking were most pronounced in the stride time and cadence parameters, with effect sizes exceeding 1.5 (Fig. 2), suggesting that treadmill walking most impedes variability in temporal rhythm. Our findings are consistent with those of Dingwell et al. [8], who similarly reported that stride time variability was reduced in treadmill walking in healthy individuals whereas mean stride times did not differ between overground and treadmill walking conditions. In contrast, Terrier and Dériaz [9] reported that stride time variability did not differ between overground and treadmill walking in healthy individuals. Such discrepancies may be accounted for by methodological differences between studies. Whereas we and Dingwell et al. [8] permitted participants to walk at preferred walking speeds (approximately 1.54 ± 0.09 m/s), Terrier and Dériaz [9] constrained walking speed to an imposed speed of 1.25 m/s. Imposing slower than preferred walking speeds may influence stride time variability [20].

Moreover, our findings demonstrated substantial effect sizes exceeding 0.7 for the peak sagittal and frontal trunk velocity variability measurements (Fig. 2), providing additional evidence that treadmill walking induces invariant gait patterns. Similar to our stride time and cadence parameters, our findings that treadmill walking reduces short- and long-term variability in peak trunk velocity parameters largely agree with results of Dingwell et al. [8], who reported that variability in sagittal plane trunk accelerations were significantly greater in overground than treadmill walking. While trunk movements are not traditionally reported in studies of spatiotemporal gait mechanics, there is a growing body of research exploring trunk control during gait. Van Emmerik et al. [21], for example, provided evidence that impaired coordination of frontal plane trunk movements may affect lateral stability during gait in older individuals. More recently, Gimmon et al. [22] provided evidence that older adults were less able to modify trunk motions to variations in walking speed than younger adults who demonstrated more adaptable trunk motion behaviors. Within context of the loss of variability hypothesis described by Lipsitz and Goldberger [18], gait training with a modality such as a treadmill that reduces trunk motion variability may be counterproductive in patient populations with gait abnormalities.

Several limitations may have affected our study. While our findings share some similarities with other studies [2,5,8], our comparisons of traditionally measured mean values across multiple spatiotemporal gait parameters conflict with other studies reporting increased cadence, decreased stride time, and decreased step length on a treadmill [1,3,4,6,23]. Our findings may be due, in part, to the treadmill experience of our participants. Since all were healthy and experienced treadmill users, they may not have required an accommodation phase on the treadmill, a phase that may have accounted for altered spatiotemporal gait parameters reported in other studies. Matsas et al. [3] and Lavcanska et al. [23] both reported, for example, that spatiotemporal gait parameters stabilized and were similar to overground walking only after walking for at least 6 min on the treadmill; data collected earlier in the testing periods were characterized by higher cadences and shorter step lengths than observed in overground walking [3]. Moreover, while our study demonstrates that a motorized treadmill diminishes stride-to-stride variability across multiple gait parameters, the underlying mechanisms for our findings are not clear. A motorized treadmill, on one hand, imposes a constant speed and may mechanically constrain the user to walk along a straighter path than during overground walking. On the other hand, within-stride variations in belt speed do occur when forces are attenuated at initial contact and can contribute to alterations in gait kinematics [24]. Furthermore, the optic flow experienced on a treadmill is distinctly different than the optic flow experienced while walking overground. Varying optic flow patterns alter locomotor control strategies [25]; therefore, our findings may reflect alterations in neural input that manifest as changes in locomotor output. Last, the hallway in which overground data collection took place was in a large hospital rehabilitation unit. While data collection was scheduled to take place during low patient-use times to minimize distractions and obstacles in the hallway and our data processing algorithms filtered outlier data from the overground walking trials, hospital personnel and patients were occasionally present in the hallway during data collection. These distractions may have influenced participants' variability during overground walking. Nevertheless, whether the reduced variability observed on a treadmill was a function of our sample, a function of mechanical constraints imposed by a motorized treadmill, a function of modifications in neuromuscular control or a function of the testing environment, it is clear that treadmill walking induced less variant gait patterns than overground walking. Investigators using motorized treadmills to study gait and clinicians using motorized treadmills for rehabilitation purposes should recognize those deviations.

5. Conclusion

Our findings imply that walking on a treadmill differs from walking overground. When traditional mean values of multiple spatiotemporal gait parameters were compared, no differences were apparent between overground and treadmill conditions. On examination of variability in those same parameters through nonlinear Poincaré analyses, however, treadmill ambulation produced less variant gait than was observed in overground walking. An implication of our findings is that invariant gait patterns imposed by treadmill training may impact one's ability to translate locomotor skills gained on a treadmill to overground walking conditions.

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Conflict of interest

None of the authors has a financial or personal relationship with people or organizations that could inappropriately influence this work.

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