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Treadmill walking is not equivalent to overground walking for the study of walking smoothness and rhythmicity in older adults

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ABSTRACT

Treadmills are appealing for gait studies, but some gait mechanics are disrupted during treadmill walking. The purpose of this study was to examine the effects of speed and treadmill walking on walking smoothness and rhythmicity of 40 men and women between the ages of 70-96 years. Gait smoothness was examined during overground (OG) and treadmill (TM) walking by calculating the harmonic ratio from linear accelerations measured at the level of the lumbar spine. Rhythmicity was quantified as the stride time standard deviation. TM walking was performed at two speeds: a speed matching the natural OG walk speed (TM-OG), and a preferred TM speed (PTM). A dual-task OG condition (OG-DT) was evaluated to determine if TM walking posed a similar cognitive challenge. Statistical analysis included a one-way Analysis of Variance with Bonferroni corrected post hoc comparisons and the Wilcoxon signed rank test for non-normally distributed variables. Average PTM speed was slower than OG. Compared to OG, those who could reach the TM-OG speed (74.3% of sample) exhibited improved ML smoothness and rhythmicity, and the slower PTM caused worsened vertical and AP smoothness, but did not affect rhythmicity. PTM disrupted smoothness and rhythmicity differently than the OG-DT condition, likely due to reduced speed. The use of treadmills for gait smoothness and rhythmicity studies in older adults is problematic; some participants will not achieve OG speed during TM walking, walking at the TM-OG speed artificially improves rhythmicity and ML smoothness, and walking at the slower PTM speed worsens vertical and AP gait smoothness.

1. Introduction

Reduced walking smoothness and rhythmicity indicate an increased fall risk among older adults [1–3], making these variables important for quantifying function. The use of treadmills for such studies is appealing, since turning corners while walking disrupts gait smoothness [4] and long, straight walking trials improve the precision of acceleration variables [4,5]. The use of treadmills to study gait function may be appropriate for some variables, since they are equivalent between overground and treadmill walking, including kinematic variability [6] and long term stride interval dynamics [7]. However, walking on a treadmill causes an increased step width [8–10], and energy expenditure [9–13] while disrupting walking coordination [14], kinematics [15–19], and kinetics [13], making these aspects of gait function appear to be *worse* than actual function during overground walking. Additionally, treadmill walking increases cadence [14], stability [6,20] and rhythmicity [20] while reducing variability [6,8,20], which would cause these aspects of gait function to appear to be better on a treadmill than actual function during overground walking [20]. It is unknown how treadmill walking affects gait smoothness and rhythmicity of older adults; it is possible that these variables could be over- or under-estimated on the treadmill for older adults, causing inaccurate functional assessments.

Treadmill-induced changes in walking function may be due to altered optic flow [21], perceived instability [8], a constrained walking speed [6], and intra- and inter-stride variations in the treadmill belt speed [22], which may increase the cognitive load of treadmill walking. A secondary task paradigm is used to study the cognitive challenge of walking, as it appears to disrupt the automaticity of gait [1]. A dual task condition can reveal early mobility difficulties of healthy older adults, such as worse smoothness as indicated by a reduced harmonic ratio [4], but walking speeds slower than the preferred walking speed also reduce the harmonic ratio [23], and slower speeds of walking are common with both treadmill walking [11] and dual-task conditions [4,24]. It is unclear whether treadmill

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walking imposes a cognitive challenge in the same way as dual-tasking.

Though gait smoothness has been evaluated using treadmill walking [25,26], its equivalency with overground walking is unknown. Many seniors cannot match their overground walking speed on a treadmill without using the handrails [19], making a slower preferred treadmill walking speed necessary [11], though slower walking worsens gait smoothness and rhythmicity [23]. To our knowledge, it is unknown if rhythmicity, represented by stride or step time variability [27], is altered for older adults on the treadmill, as it is for young adults [20], and it is unknown whether treadmill walking for older adults adds a cognitive load that disrupts these variables similarly to a divided attention task. Therefore, the purpose of this study was to determine if treadmills can be used to reflect natural overground walking for the study of gait smoothness and rhythmicity in older adults, and if it is disrupted, whether it is similar to the disruption posed by a dual-task condition. We hypothesized that (1) gait smoothness and rhythmicity would be equal during treadmill and overground walking at the same speed, but (2) worsened (lower harmonic ratio, higher stride time variability) when walking at a slower preferred treadmill speed, and (3) the slower preferred treadmill speed would cause equal smoothness and rhythmicity to a condition involving a divided attention task during overground walking.

2. Methods

2.1. Participants

The study was approved by our Institutional Review Board and participants provided written informed consent. Forty men and women (age range: 70–96 years, Table 1) were recruited using the local newspaper and retirement facilities, and were community-dwelling or lived in condominiums or apartments in the retirement communities. One participant was excluded as a high functioning outlier based on scores being more than 2.5 standard deviations (SD) from the group mean. The inclusion criteria were age of at least 70 yrs, ability to walk overground and on a treadmill without an assistive device and while not holding onto the treadmill handrails, repeatedly sit and stand from a chair, and use stairs while free of muscle, bone or joint pain due to medical conditions or medications, able to travel to one of our testing sites, and intact cognitive function (Mini-Mental State Examination score > 23). Participants self-rated their health as good (23.1%), very good (51.3%), or excellent (25.6%), reported taking an average of 2.3 (standard deviation: 2.1) medications for chronic conditions (range: 0–7 medications, median: 2.0 medications), and 12 (30.7%) reported having experienced a fall within the past 12 months.

Table 1
Participant Characteristics (mean (SD) where applicable).

	Full sample ($n = 39$)	Participants who completed TM-OG condition ($n = 29$)	Participants who did not complete TM-OG condition ($n = 10$)
Age	80.6 (6.5)	79.10 (5.89)	84.00 (7.00)*
Sex (% Fem.)	59%	55.2%	70%
Height (m)	1.68 (0.10)	1.69 (0.09)	1.62 (0.21)
Body mass (kg)	72.3 (16.7)	73.32 (16.94)	69.46 (16.73)
BMI (kg/m^2)	25.6 (3.9)	25.67 (4.23)	25.73 (4.10)
Grip Strength (kg)[a]	61.0 (40.73)	69.0 (39.0)	50.5 (19.0)*
TUG (s)[a]	8.72 (2.13)	8.25 (1.83)	10.51 (2.59)*
SPPB (points)[a]	1.04 (0.08)	11.0 (2.0)	9.50 (1.00)*
ABC (%)[a]	96.56 (5.60)	96.88 (2.75)	88.91 (13.75)*
Number of people who fell in the past year	12 (30.8%)	8 (27.6%)	4 (40.0%)
Current regular or occasional TM user	46.2%	48.3%	40%
Regular or occasional TM use in the past	25.6%	27.6%	20%
Little or no prior TM experience	25.6%	24.1%	40%

Different between sub-groups: * $p < 0.05$

[a] median and interquartile range presented for non-normally distributed variables.

2.2. Procedures

Testing was conducted at three locations, a fitness center and two local retirement facilities. Participants completed an interview regarding their fall history within the past year, health history, and activities-specific balance confidence (ABC), followed by a hand grip strength test, the 8-ft Timed Up and Go (TUG) and Short Physical Performance Battery (SPPB) to characterize their physical function. Participants walked overground and on a treadmill during a single testing session. Given that the testing was conducted at different sites, different treadmills were used; each had handrails, were set to 0% incline, and did not include a safety harness, but included safety stop tethers that were attached to the participants while not interfering with natural movement.

Four indoor walking conditions were conducted; two were overground and two were on a treadmill. The overground trials were completed over a distance of 22.9–25.7 m and a walkway width varying from approximately 2 m to the width of a gym, depending on facility constraints. The first overground condition was at a self-selected natural walking speed (OG), and the second involved a dual-task (OG-DT) of counting in reverse by five from a randomly selected integer greater than 100 and divisible by five. Walking speed was calculated by dividing the distance walked by the time it took to cross the distance. In order to be at their comfortable walking speed within the testing distance, participants began walking approximately two meters prior to the start line and kept walking two meters beyond the finish line.

Following the two OG conditions, two one-minute treadmill (TM) walking conditions were conducted following a familiarization period, which involved determining the preferred treadmill speed over about 5 min. Part of the familiarization procedure was to become accustomed to walking without the handrail, given the effect it has on stride interval dynamics [7]. Two speeds were conducted on the treadmill: the average overground speed (TM-OG) and a preferred treadmill walking speed (TM-PWS). In order to experience the OG speed on the treadmill, it was necessary to always conduct overground prior to treadmill conditions. TM-PWS was conducted because self-selected walking speed on the treadmill is slower than OG walking [11], and many older adults are unable or unwilling to complete the TM-OG condition, due to it feeling too fast [19]. Indeed, only 29 of the 39 participants were willing to have the treadmill speed increased to their OG walking speed. TM-PWS was identified by averaging the upper and lower bounds of comfortable walking speed [28] by gradually increasing and decreasing the speed until the upper and lower boundary speeds for comfortable walking on the treadmill were consistently identified as being ‘uncomfortably fast’ or ‘uncomfortably slow,’ and there was not a difference of more than 0.2 mph (0.32 km/h) between the repeated trials of the upper or lower boundaries [28]. Participants were blinded to the treadmill speed. TM-PWS was calculated as the average of the mean upper and lower speeds of the comfortable range.

2.3. Instrumentation

Participants were instrumented with a triaxial accelerometer (G-Link® -LXRS® Wireless Accelerometer Node, LORD MicroStrain

Sensing Systems) taped to the skin overlaying the 4th lumbar vertebra. While the participant stood in a neutral position, the accelerometer sensor was aligned in the frontal plane using a bubble level, to reduce the amount of left or right tilt. Data were streamed wirelessly to the computer from the sensor, and sampled at 200 Hz.

2.4. Signal Processing

Signal analysis was conducted using custom written code in Matlab R2013a software. The acceleration signals were filtered with a 4th order Butterworth filter with a cut-off frequency of 15 Hz. The acceleration due to gravity was subtracted out of the signal for each axis; it was assumed that the mean acceleration for each axis was zero, since participants walked in a straight line, and the analysis did not include the first two steps of speeding up and the last two steps of slowing down [29]. This mean acceleration was subtracted from the signal for each axis in order to improve the estimate of the translational accelerations during the trials.

Individual steps were determined using the AP peak magnitude, which coincides with heel contact [3,29]. The AP peaks (Fig. 1) were selected using an algorithm supplemented with a graphical user interface to ensure that a consistent peak was selected for irregular trials. The first & last two steps of the OG trials were excluded from the analysis. The TM trials analysis was restricted to the same number of steps as occurred during the participant's OG trial and were restricted to steps occurring in the middle of the TM trial. Stride time was calculated as the time elapsed between every other step. The rhythmicity of gait, or the consistency of the stride time within a trial, was quantified as the standard deviation (SD) of stride time (STSD) for each trial. A lower STSD indicates less stride time variability and improved ability to maintain a consistent temporal rhythm during walking.

The harmonic ratio, a measure of the smoothness or symmetry between the two steps within a stride, is calculated separately for the vertical, AP, and ML axes from accelerometer sensors placed on the trunk [2,3,28]. It is a comparison of acceleration cycles that are in-phase with the primary stride frequency to cycles that are out-of-phase. A higher harmonic ratio represents smoother walking, since this indicates that accelerations are in-phase with the primary oscillations of the stride. A Fourier transform was used to reduce the acceleration signals to the first 10 harmonics [29] defined by harmonic number and amplitude over a period of one stride. Since there are two steps within a stride, vertical and AP accelerations are biphasic over a stride, making the 2nd harmonic dominant and the even harmonics in-phase (Fig. 2) [29]. The AP and vertical harmonic ratios were calculated as the sum of the even divided by the sum of the odd harmonic amplitudes. The calculation was the inverse for the ML signal, since it is monophasic over one stride, making the 1st harmonic dominant and the odd harmonics in-phase [29]. The harmonic ratio was calculated for each stride and averaged for each trial.

2.5. Statistical analysis

The statistical analysis was performed using Systat 13. Normality of the data was evaluated using the Kolgomorov-Smirnof and Shapiro-Wilk tests. A repeated measures ANOVA was conducted to compare (1) gait speed between all conditions, and (2) the harmonic ratio (ML, AP, vertical) between OG, OG-DT, and TM-PWS

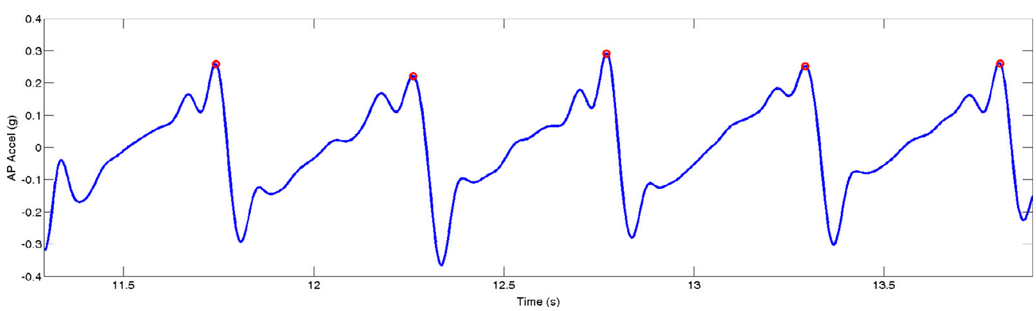

Fig. 1. An example anterior-posterior acceleration (AP Accel) signal of five steps from one participant during Overground (OG) walking. Circles indicate peaks in the AP acceleration used to determine the onset of a new step.

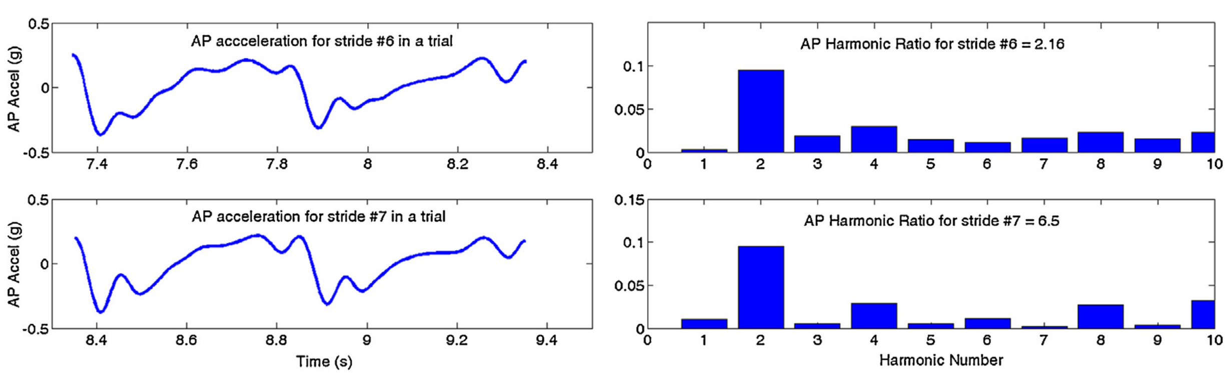

Fig. 2. The left column displays anterior-posterior accelerations (AP Accel) over the course of a stride from heel strike to heel strike of the same foot for two strides, stride #6 (top) and stride #7 (bottom), within a representative trial. The right column displays the amplitudes of the first 10 harmonics generated by a Fourier transform for the strides displayed on the left. The biphasic pattern characteristic of the AP acceleration signal, due to two steps occurring within a stride, illustrates that the even harmonics should be dominant during smooth walking. The bottom figure (stride #7) represents a stride where the even harmonics have a higher amplitude than the odd harmonics, resulting in a smoother stride and a higher harmonic ratio. In the top figure (stride #6), the two steps within the stride are less symmetrical, resulting in less smooth walking and a lower harmonic ratio.

trials, involving the 39 participants who completed each of these conditions. Post hoc tests were performed with Bonferroni correction. The Wilcoxon signed-rank test was used to compare the following non-normally distributed variables: (1) the harmonic ratio (ML, AP, vertical) between OG and TM-OG trials for the 29 participants who completed the TM-OG condition, since the TM-OG data and OG data for this smaller group were not normally distributed, (2) the differences between conditions for the STSD, and (3) the difference in the number of falls, grip strength, ABC, TUG, and SPPB functional tests of the participants who completed the TM-OG condition and those who did not.

3. Results

Compared to OG walking, TM-OG matched walking speed ($p > 0.05$, Table 2), did not affect AP and vertical harmonic ratio, but increased ML harmonic ratio and decreased STSD ($p < 0.05$, Table 2, Fig. 3). Compared to OG walking, TM-PWS reduced walking speed and reduced the vertical and AP harmonic ratio ($p < 0.05$, Table 2, Fig. 3), but did not affect ML harmonic ratio or STSD. Compared to OG walking, OG-DT reduced walking speed ($p < 0.05$, Table 2), caused a trend toward reduced vertical harmonic ratio ($p = 0.088$, Fig. 3), reduced AP and ML harmonic ratio, and increased STSD ($p < 0.05$, Table 2). Compared to OG-DT walking, TM-PWS reduced walking speed ($p < 0.001$, Table 2), caused a trend toward reduced AP harmonic ratio ($p = 0.059$, Fig. 3), but had lower STSD ($p < 0.05$, Table 2).

Table 2
Mean (SD) walking speeds, Harmonic Ratio (HR), and median (SD) STSD for Overground (OG), Treadmill walking at Overground pace (TM-OG), Overground with Dual-Task (OG-DT), and Treadmill walking at preferred treadmill walking speed (TM-PWS).

	OG ($n=39$)	TM-OG ($n=29$)	OG-DT ($n=39$)	TM-PWS ($n=39$)
Walking speed (m/s)	1.27 (0.17)	1.32 (0.17)	1.19 (0.21)*	1.05 (0.30)**, ^
Vertical HR	3.63 (0.75)	3.57 (0.89)	3.33 (0.67) a	2.97 (0.87)**
AP HR	3.54 (0.9)	3.7 (0.92)	3.23 (0.8)*	2.88 (0.94)**, b
ML HR	2.41 (0.71)	2.75 (0.8)*	2.22 (0.58)*	2.39 (0.62)
STSD (s)	0.025 (0.028)	0.015 (0.013)*	0.037 (0.033)**	0.025 (0.019)^

Different than OG speed: * $p < 0.05$, ** $p < 0.001$, a trend where $0.05 > p < 0.10$
Different than OG-DT: ^ $p < 0.005$, b trend where $0.05 > p < 0.10$

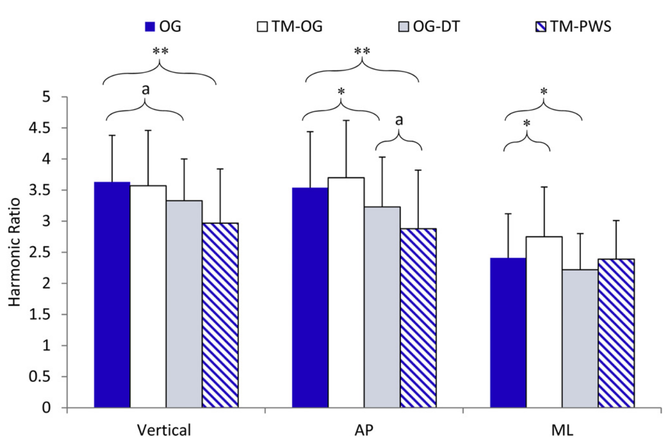

Fig. 3. Average harmonic ratio for each axis and condition with error bars of standard deviation for Overground (OG, $n = 39$), Overground Dual-Task (OG-DT, $n = 39$), Treadmill at treadmill preferred walking speed (TM-PWS, $n = 39$), and Treadmill walking at Overground Speed (TM-OG, $n = 29$).
*$p < 0.05$, ** $p < 0.001$, a trend where $0.05 > p < 0.10$

Participants who completed TM-OG had equal weight, height, BMI, and number of falls in the past year ($p > 0.05$), but they were younger and had greater grip strength and higher scores on the ABC, TUG, and SPPB functional tests ($p < 0.05$) than participants who did not complete TM-OG (Table 1). Only four of the 10 who did not complete TM-OG resided in the retirement communities; the remainder responded to newspaper ads and were tested at the fitness facility.

4. Discussion

TM walking was not comparable to OG walking for walking smoothness and rhythmicity, and the differences did not mirror the effect of walking with divided attention. Only higher functioning participants could complete TM walking while matching a natural OG speed (TM-OG), and for these participants, TM-OG preserved vertical and AP gait smoothness, but it improved ML gait smoothness, as indicated by the increased ML harmonic ratio. It also improved rhythmicity, as revealed by the reduced STSD, consistent with the results of previous research with young adults, where STSD was lower during TM walking [20], perhaps reflecting the imposed pace of the TM. ML harmonic ratio was higher during TM-OG than OG walking, and while we did not measure step width in the current study, it is likely that it was larger [8] to increase stability on the treadmill in response to its relatively narrow and raised walking platform. An increased ML harmonic ratio is consistent with previous findings that step width is larger and less variable during treadmill walking than overground walking at the same pace [8], since the harmonic ratio is increased if the two steps within a stride are more consistent with each other. The TM-OG results would appear to indicate better function during TM walking than their actual function during overground walking, however, the TM-OG condition is not possible for lower functioning participants who cannot reach this speed on the TM, which included more than 25% of our sample, and so the TM-OG results pertain only to the higher functioning seniors in our sample.

At a comfortable treadmill walking speed (TM-PWS), which was slower than OG speed, ML smoothness was maintained, but vertical and AP gait smoothness were worsened, as indicated by the reduced harmonic ratio, and consistent with previous research that gait smoothness worsens with reduced gait speed [23]. The harmonic ratio during OG walking in the present study compares well with the magnitudes found in previous studies for young adults [4] and for higher functioning older adults [2,29], however, the TM-PWS condition reduced the harmonic ratio to the level seen in older adults with high fall risk in a previous study, where, for example, the AP harmonic ratio was 2.79 (SD 1.03) during OG walking [2]. This suggests that evaluations of gait smoothness on the treadmill at a preferred walking speed would cause participants' function to appear worse than if measured during OG walking, which could result in inaccurate functional assessments.

Participants exhibited less gait rhythmicity during the OG trial with a dual task (OG-DT), which had the highest STSD of all conditions, consistent with some, but not all previous studies of temporal variability during dual-task walking with healthy older adults [30]. The TM-PWS STSD was the same as OG walking and less than the OG-DT condition, meaning better rhythmicity than during OG-DT. The OG-DT condition reduced walking smoothness, similar to previous work with both young and older adults [4], and there was a trend for AP smoothness during TM-PWS to be even less than during OG-DT, perhaps reflecting the additional effect of slower walking speed during TM-PWS compared to OG-DT. That the results of TM-PWS did not mirror those of OG-DT indicate that the reduced smoothness of the TM-PWS condition is probably not due to an equivalent cognitive load imposed by the treadmill environment, at least not similar to backwards counting, but rather is likely due in large part to the effect of reduced walking speed [23] and perhaps kinematic and kinetic changes evoked by treadmill walking [13–19]. Our findings and others' [4] indicate that dual-task conditions reduce gait smoothness likely due to the effects of both reduced walking speed and divided attention. If a cognitive challenge were to be performed while walking on the treadmill, we anticipate that rhythmicity would be worsened and similar to OG-DT and smoothness would be worsened beyond TM-PWS; this is a condition we did not conduct without a safety harness and due to uncertainty regarding which speed would be appropriate. This would likely be slower than TM-PWS.

Limitations of the study include conducting data collections at multiple sites, involving multiple treadmills that may be different regarding, for example, how much the belt speed changes between steps, the damping properties, and the visual effect of the handrail and console configuration and surrounding environment. These results are limited to the use of a treadmill without holding on to the handrails. Some aspects of gait may continue to change during a longer treadmill familiarization period for older adults [19]. The participants completed the overground walking trials prior to the treadmill trials, in order to include the overground speed on the treadmill. This meant that the order of the conditions could not be randomized, which introduces the possibility that participants could be systematically fatigued during the treadmill trials, though the number of walking trials was small.

In conclusion, treadmill walking should not be considered as equivalent to overground walking for the study of gait smoothness and rhythmicity in generally healthy and self-ambulatory older adults.

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Conflict of interest statement

We have no conflicts of interest.

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