Uneven surface and cognitive dual-task independently affect gait quality in older adults

Abstract

Background Real-world mobility involves walking in challenging conditions. Assessing gait during simultaneous physical and cognitive challenges provides insights on cognitive health. **Research question** How does uneven surface, cognitive task, and their combination affect gait quality and does this gait performance relate to cognitive functioning? **Methods** Community-dwelling older adults (N=104, age=75±6 years, 60% females) performed dual-task walking paradigms (even and uneven surface; with and without alphabeting cognitive task (ABC)) to mimic real-world demands. Gait quality measures [speed(m/s), rhythmicity(steps/minute), stride time variability (%), adaptability (m/s^2), similarity, smoothness, power (Hz) and regularity] were calculated from an accelerometer worn on the lower back. Linear-mixed modelling and Tukey analysis were used to analyze independent effects of surface and cognitive task and their interaction on gait quality. Partial Spearman correlations compared gait quality with global cognition and executive function. **Results** No interaction effects between surface and cognitive task were found. Uneven surface reduced gait speed(m/s) (β=-0.07). Adjusted for speed, uneven surface reduced gait smoothness (β=-0.27) and increased regularity (β=0.09), Tukey *p<.05*, for even vs uneven and even-ABC vs uneven-ABC. Cognitive task reduced gait speed(m/s) (β=-0.12). Adjusted for speed, cognitive task increased variability (β=7.60), reduced rhythmicity (β= -6.68) and increased regularity (β=0.05), Tukey *p<.05,* for even vs even-ABC and uneven vs uneven-ABC. With demographics as covariates, gait speed was not associated with cognition. Gait quality [lower variability during even-ABC (ρ_p=-.31) and uneven-ABC (ρ_p=-.28); greater rhythmicity (ρ_p between .22 and .29) and greater signal-adaptability AP (ρ_p between .22 and .26) during all walking tasks] was associated with better global cognition. Gait adaptability during even (ρ_p=-0.21, p=0.03) and uneven(ρ_p=-0.19, p=0.04) walking was associated with executive function. **Significance** Surface and cognitive walking tasks independently affected gait quality.

Our study with high-functioning older adults suggests that task-related changes in gait quality are related to subtle changes in cognitive functioning.

Keywords: Gait, Cognitive function, Healthy aging, Accelerometry, Dual tasks

Introduction

Limitations in community mobility of older adults is a growing global concern. Walking in real-world environments requires adequate cognition to multi-task such as walking while talking, navigating traffic, crossing a road and making a turn. Additionally, walking on uneven terrain such as grass, gravel and poor-quality sidewalks are common in community environments and requires adequate gait adaptation [1]. Dual-task and uneven surface walking paradigms can mimic attentional and challenging physical demands in navigating real-life environments [2]. Often, these physical and cognitive challenges are navigated simultaneously to enable walking in natural environments.

Quantitative aspects of walking that provide complementary knowledge on overall 'gait quality' can be quantified (Dasgupta [3], review). These gait aspects include pace (or speed), variability, rhythmicity, adaptability, similarity, smoothness, power, and regularity. Gait quality aspects beyond pace ~~speed~~ may be useful in capturing the motor control strategies and related cognitive function important in successful everyday walking in natural environments [4], [5]. Gait measures such as pace ~~speed~~, variability and rhythmicity assessed during dual-task walking are shown to be more closely associated with everyday walking, in comparison to gait measures from walk-only task [6]. Prior studies have demonstrated that during cognitive dual-task walking, compared to single-task walking gait speed slows, cadence reduces, variability increase, and entropy rate increases [4], [7], [8]. Challenging walking surfaces are associated with reduced walking smoothness [9], increased variability, and unchanged complexity [8].

Research has shown that the ability to walk can be explained by participant characteristics and motor factors. Walking involves cognitive processes, particularly during dua-task walking i.e. while performing a complex cognitive task while walking [10]. Gait performance during dual-task conditions reveal stronger associations to health characteristics such as cognition [11]. Executive attention and processing speed predicted variance in dual-task step time [12]. Pace, stepping length and time, knee angle, and smoothness were found to be able to detect older adults with poor global cognitive function [13], [14],

[15], [16]. It is difficult to compare and draw parallels between studies since there are variations in the difficulties of cognitive tasks being performed, and the methods to capture gait are different as well. Limited research on accelerometer-based gait measures in relation to cognition has been reported. Assessing gait (beyond speed) on uneven terrain combined with a cognitive task can help in identifying individuals at risk of experiencing cognitive decline, falls and gait disabilities [17], [18]. However, research is lacking in the realm of gait performance during combined surface and cognitive tasks. For example, does cognitive dual-task provide unique information if performed on uneven surface, or it is redundant to what is already being conveyed from cognitive dual-tasking on an even surface?

Furthermore, the mechanisms underlying the effects of surface versus cognitive tasks may be different. Walking on uneven terrain compared with smooth terrain could contribute to greater energy expenditure due to adjusting of step parameters such as variability [19]. The framework of automaticity versus executive processing also becomes important in context of unexpected changes during walking conditions [20]. Crucial information from periphery integrates quickly into the ongoing gait cycle via automaticity of control. In contrast, an executive control strategy would require a longer time and processing before integration in gait pattern, thus acting as more of a compensatory control strategy. Dual-task walking is the most widely used approach for probing automatic versus executive control [20].

In this study, we examine gait quality of older adults in four conditions – a) even surface walking (even), b) uneven surface walking (uneven), c) dual-task walking while reciting alternate alphabet letters on even surface (even-ABC) and d) dual-task walking on uneven surface (uneven-ABC). Gait adjustment during complex walking tasks, may even reveal an individual's cognitive abilities, which we intend to investigate. The two objectives and corresponding hypotheses were to 1) describe the effects of surface (even versus uneven) and cognitive task (absence versus presence) on accelerometer measures of gait quality; 2) determine the association of gait quality during the four walking conditions with global cognition and executive functioning. We hypothesized that aspects of gait quality will be negatively impacted by uneven surface and cognitive task. Our overall hypothesis is that gait requires cognitive resources and that physical and cognitive challenges impact measures of gait and cognition. Thus, cognitive challenges would reduce cognitive resources and thereby impact metrics of gait. Additionally, we expect that the cognitive challenge performed on an uneven surface will be a more challenging gait task, and hence, there would be an even greater impact on aspects of gait (i.e., there would be an interaction effect). We also hypothesized that better gait quality (defined as greater walking pace ~~speed~~, lower variability, greater adaptability, greater rhythmicity, greater smoothness, greater power and a lower regularity) will be associated with better cognitive function. Additionally, we hypothesized that these associations are stronger for dual-task conditions compared to single task walking.

Materials and Methods

Study Design and Participants.

Community dwelling older adults based in Pittsburgh, USA participated. Baseline data from three studies were utilized (Neural Mechanisms of Community Mobility, NMCM (n=29), Program to Improve Mobility in Aging – Near Infrared Spectroscopy sub-study, PRIMA-NIRS (n=42) and Move Monogahela-Youghiogheny Healthy Aging Team, MoveMYHAT (first n=46 enrolled in the study)). The NMCM study aims to study brain function with relation to navigating challenges experienced while walking in the community. The PRIMA-NIRS sub-study aims to assess the effects of motor skill training on central motor control in older adults with walking difficulties. The MoveMYHAT study aims to understand walking and attention, especially the role of dopamine and sensorimotor brain network connectivity in building resilience to age-related impairments. These studies each recruited participants from parent studies [21]–[23] who were greater than 65 years old and were able to walk without assistance. Recruitment into the studies excluded those who had a history of stroke, showed symptoms of dementia, mild cognitive impairment, or presence of major motor and neurological diseases. For NMCM, the participants were classified as high risk for dementia if they had any of the following characteristics: (1) a 3MSE score of less than 80 at 1 of their last 2 clinic visits, (2) a 5-point decline in the 3MSE from the time of MRI to last contact, (3) a Telephone Interview for Cognitive Status score less than 28, (4) an Informant Questionnaire for Cognitive Decline in the Elderly score of more than 3.6, (5) an incident stroke, (6) were currently residing in a nursing home, or (7) had a diagnosis of dementia found on medical record review. [21]. For PRIMA-NIRS, likely dementia or cognitive impairment were defined as Modified Mini-Mental State Examination score (3MS) < 79 [22]. For MoveMYHAT, Participants considered moderately to severely cognitively impaired based on Clinical Dementia Rating (CDR) scale $>=1$. 11% (n=13) of participants had technical errors with accelerometry and could not be included.

Walking tasks and assessment.

The protocols for gait measures and tests performed were identical for all these studies. An accelerometer (Actigraph LLC; Pensacola, FL) placed on the lower trunk (L3 position of the lumbar spine) was used to derive objective measures of gait in three anatomical planes – mediolateral (ML), anterior-posterior (AP) and vertical (V) [24]. Four different walking conditions 1) even surface (even) 2) even surface with dual-tasking (even-ABC), 3) uneven surface (uneven) and 4) uneven surface with dual-tasking (uneven-ABC) were conducted in a pseudorandomized order and repeated four times ~~on 15 m long straightaways~~. The even surface consisted of level flooring. The uneven surface consisted of 1.5 cm high wood prisms arranged randomly at a density of 26 pieces/m^2 underneath carpeting [25]. The even and uneven surfaces were 15 m long straightaways. Participants were asked to walk at their comfortable walking pace. The alphabeting task was to recite every other letter of the alphabet out loud, starting with the letter "B" [26]. Participants were not told to prioritize one task over the other, for example, alphabeting versus walking. The details of walking tasks and experimental setup are described in [27]. Time spent walking on each surface was recorded with 20 seconds of quiet standing before each trial. Participants also separately completed the alphabeting task while standing still for 20 seconds twice interspersed among the trials. Thus, a total of 10 trials were performed for the alphabeting task – 4 during even surface walking, 4 during uneven surface walking, and 2 during standing. Alphabeting performance was calculated as rate of correct letters, i.e., count of correct letters by the time taken to complete the walking task (letters/s).

Gait accelerometry processing.

Signal processing techniques allow extraction of measures in time, frequency and information theory domains beyond traditional gait cycle metrics [28]. These characteristics of gait quality beyond gait pace may be useful in capturing the motor control strategies and related cognitive function important in successful everyday walking in natural environments. For each trial, the first two seconds of walking were not included to account for gait initiation. Accelerometer data were sampled at 100 Hz in most cases.

Accelerations from 33 (29%) subjects were sampled at 30 Hz due to technical issues at the time of data collection. These signals were upsampled to 100 Hz using MATLAB 2020b. For upsampling, we first performed zero-padding on the signal and then used anti-aliasing finite impulse response filter with a Kaiser window. The frequency content of the signal was preserved. Pre-processing included removal of outliers using a median filter of order five and normalized by the magnitude of the maximum amplitude present. Next, heel strike and toe-off for each step were identified (see [28], [29] for details). All gait acceleration measures were selected because of prior reported association of the gait quality metrics with physical function [3], [30], [31]. Gait quality metrics were calculated, including variability (stride time coefficient of variation), rhythmicity (cadence), adaptability (standard deviation of signal acceleration amplitude AP [32]), similarity (cross-correlation AP-V [33], [34]), smoothness (harmonic ratio AP [35]), power (peak frequency V), and regularity (entropy rate ML [36],[37]). See references for details on gait measures [38], [39]. For uniform scaling of the measures, the gait variables were normalized by subtracting mean and dividing by standard deviation.

Demographic and Cognitive Health Characteristics.

Descriptive characteristics (age, sex, race and education) were recorded as self-report. Height and weight were measured using standard procedures and body mass index (BMI) was computed. Mini-Mental State Exam (MMSE) was used to assess global cognition [40]. PRIMA-NIRS study used Modified Mini-Mental State Exam, later converted to MMSE using the appropriate item scores. We took only the Mini-Mental State Exam (MMSE) equivalent questions from the Modified Mini-Mental State Exam (3MS) to calculate the MMSE scores. One person performed this conversion, and no difficulties were experienced. Trail Making Tests Part A and Part B were used to assess executive functioning and working memory [41]. Both Trails A and Trails B consist of 25 circles distributed over the page. Subjects are asked to complete each of the Trail Making tests as quickly as possible, connecting numbers in order for Trails A and alternating numbers and letters in order for Trails B. The maximum allowable time cut-offs for the three studies were different but no participant from any study exceeded the shortest maximum allowable time (90s for Trails A and 240s for Trails B).

Statistical analysis

Effects of surface and cognition on gait (objective 1)

Linear mixed effects models were used to study the effect of surface and cognition on gait variables (equation 1). Independent variables were surface, cognition and their interaction. Gait speed during even walking, age, sex, and BMI were used as fixed effect covariates. Participants were assigned as random effects also accounted (1|subject), following Wilkinson notation [42]. Dependent variables were the gait metrics, each evaluated with a separate model. Post-hoc Tukey pair-wise analysis was conducted to compare across the four to further elucidate the effects seen in the primary analysis.

$$\text{Gait variables} \sim \beta_0 + \beta_1\text{Surface} + \beta_2\text{Cognition} + \beta_3\text{CognitionXSurface} + \beta_4\text{gait speed (even walking)} + \beta_5\text{age} + \beta_6\text{sex} + \beta_7\text{BMI} + (1|\text{subject}) \quad (1)$$

Tukey analysis was conducted to compare pairs of tasks, specifically, even vs uneven, even-ABC vs uneven-ABC, even vs even-ABC, and uneven vs uneven-ABC. By these comparisons, we aim to deduce detailed effect of specific control conditions for example, does cognitive dual-task provide unique information if performed on uneven surface, or it is redundant to what is already being conveyed from even vs even-ABC?

Association of gait with cognitive function (objective 2)

Partial Spearman correlations were used to assess associations of the gait metrics with the cognitive measures (MMSE, Trail Making Test A, and Trail Making Test B) under the four conditions. Spearman does not require the variables to have an approximate normal distribution. Spearman correlations are more robust to outliers. Another advantage is that this rank based correlation works well when the variables are either continuous (such as time taken to perform trail making tests) or ordinal (MMSE scores). So, for the sake of uniformity, we computed Spearman correlations between gait variables and cognitive scores. Partial scores were used to account for covariates - age, sex, BMI, education, and gait speed. For assessing associations between gait pace ~~speed~~ and cognition, we used age, sex, BMI, and education as covariates. For other variables, gait pace ~~speed~~ was used as an additional covariate. Bonferroni correction was performed to correct for multiple comparisons during correlation analyses of gait parameters with cognition measures.

All statistical tests (Linear mixed models, correlations, Tukey, Bonferroni) were conducted using libraries and toolkits offered in Python 3.8 such as ‘statsmodels’, ‘SciPy’, and ‘pingouin ’.

Results

The sample included 104 older adults with mean age 75 (STD 6 years), 62 (60%) females. Participants were highly educated with 78 (75%) individuals having more than high school education, and were predominantly White (n=89, 85%). **Table 1** presents the demographic, cognitive function, and alphabeting performance for the participant population. The effects of the demographic variables on gait variables were not significant (**Supplementary Table 1**).

Table 1. Participant demographics, cognitive function, and alphabeting performance and gait performance (N=104).

Variable	**Mean ± STD or n (%)**
Demographics	
Age (years)	75 ± 6
Sex (females)	62 (60%)
Body Mass Index (kg/m^2)	28.56 ± 4.92
Race (White)	89 (85%)
Education (> 12 years)	78 (75%)
Cognitive function	
Mini-Mental State Exam	28.6 ± 1.7
Time taken to do trail making test A (s)	31.0 ± 11.0
Time taken to do trail making test B (s)	80.0 ± 34.8
Performance on alphabeting cognitive task	
Rate of correct letters during standing (/s)	.56 ± .19
Rate of correct letters during Even-ABC (/s)	.61 ± .18
Rate of correct letters during Uneven-ABC (/s)	.58 ± .18

Gait quality aspects

The average walking pace ~~gait speed~~ of the participants on even surface was 0.97 ± 0.17 m/s. Gait aspects were not highly correlated with each other ($\rho<.60$) during even walking tasks (**Supplementary Fig. 1**). The effect of gait pace ~~speed~~ during even surface walking on all gait variables, except power, was significant (**Supplementary Table 1**).

Effect of walking tasks on gait quality aspects

Linear mixed model showed that gait quality metrics are affected by the surface condition and ABC cognitive task (**Table 2**).

Table 2. Effect of Surface change and cognition task on gait variables. Gait speed during even walking, age, sex, and BMI were used as fixed effect covariates and participants were used as random effect covariate. β (95% CI) are reported (N=104), **p<.001, **p<.01*

Gait aspect	Gait variable	Surface β (95% CI)	Cognition β (95% CI)	Surface X Cognition β(95% CI)
Pace	Gait Speed (m/s)	-0.07 (-0.08, -0.06)**	-0.12 (-0.13, -0.11)**	0.02 (-0.01, 0.04)
Variability	Stride time CoV (%)	3.27 (0.91, 5.64)*	7.60 (5.24, 9.96)**	0 (-3.42, 3.42)
Rhythmicity	Cadence (steps/minute)	-3.31 (-5.18, -1.43)*	-6.68 (-8.55, -4.80)**	-0.74 (-3.39, 1.91)
Adaptability	Standard deviation AP (m/s^2)	0.01 (0.01, 0.02)**	-0.01 (-0.02, -0.01)**	0 (-0.01, 0.01)
Similarity	Cross-correlation AP-V	-0.05 (-0.06, -0.04)**	-0.02 (-0.03, -0.01)*	0.01 (-0.01, 0.03)
Power	Peak frequency V (Hz)	-0.06 (-0.14, 0.02)	-0.14 (-0.22, -0.07)**	-0.06 (-0.17, 0.05)
Smoothness	Harmonic Ratio AP	-0.27 (-0.35, -0.19)**	-0.20 (-0.28, -0.12)**	-0.01 (-0.12, 0.11)
Regularity	Entropy Rate ML	0.09 (0.07, 0.10)**	0.05 (0.04, 0.07)**	0 (-0.02, 0.02)

Notes
CoV. Coefficient of Variation
AP. Anterior-Posterior
V. Vertical
ML. Mediolateral

No interaction effects (surface x cognition) were found, (all *p>.05*), indicating that gait aspects were not affected more than expected from the individual dual-task effects when the tasks were combined. As expected, both uneven surface and the ABC cognitive task were associated with reduced pace ($\beta_{surface}$ = -0.07, $\beta_{cognition}$ = -0.12), rhythmicity ($\beta_{surface}$ = -3.31, $\beta_{cognition}$ = -6.68), and smoothness ($\beta_{surface}$ = -0.27, $\beta_{cognition}$ = -0.20) and with increased variability ($\beta_{surface}$ = 3.27, $\beta_{cognition}$ = 7.60) and regularity ($\beta_{surface}$ = 0.09, $\beta_{cognition}$ = 0.05). Interestingly, uneven surface was associated with increased adaptability, while the added cognitive task was related to decreased adaptability, though the effect is quite small (β's ~ 0.01). Power related only to the cognitive dual-task condition effect. Cognitive task, in general, has a larger impact on gait quality aspects, specifically pace, variability, and rhythmicity ($\beta_{cognition} > \beta_{surface}$).

Follow-up pairwise Tukey analyses across the four walking tasks (even, uneven, even-ABC, uneven-ABC) within each gait measure were performed (shown in **Fig. 1**). The task comparisons included even vs uneven, even vs even-ABC, uneven vs uneven-ABC, and even-ABC vs uneven-ABC, thus including surface or cognitive tasks as one of the control conditions (Tukey, *p<.05*).

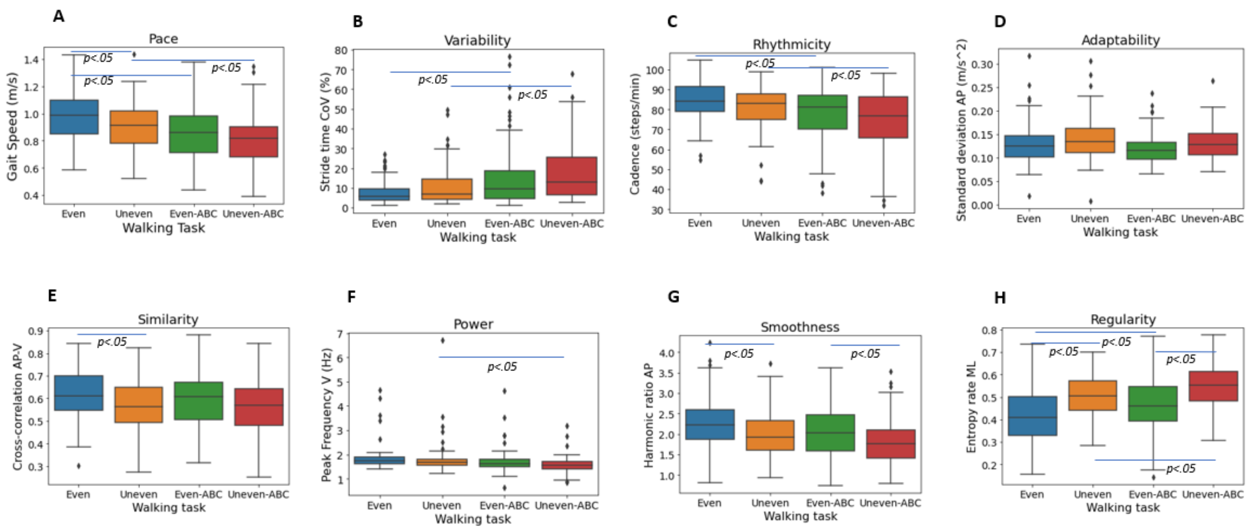

Fig. 1 Pare-wise comparisons of gait variables across the four conditions. Tukey (*p*<.05). Blue lines indicate statistically significant differences. **A)** Pace (Gait speed) reduces as the difficulty of task increases **B)** Variability (stride time variability CoV) increases due to cognitive task. The standard deviation in variability increases with task complexity. **C)** Rhythmicity (cadence) reduces due to cognitive task on both even and uneven surfaces **D)** Adaptability (standard deviation AP) is not significantly affected during dual-task walking, although it shows increased trending effects on uneven surface and decreased effects during cognitive task **E)** Similarity (cross-correlation AP-V) reduces on uneven surface **F)** Power (peak frequency V) reduces significantly due to cognitive task, the effect is stronger on even surface. **G)** Smoothness (harmonic ratio AP) reduces on uneven surface **H)** Regularity (entropy rate) increases due to uneven surface and cognitive dual-task, the effect is stronger due to surface change

In summary, smoothness reduces, and regularity increases when surface changes from even to uneven, both in the absence as well as presence of alternate alphabeting task (cognitive task). On the other hand, variability (%) increases, rhythmicity (steps/min) reduces, and regularity increases when an alternate alphabeting task (cognitive task) is added, both on even as well as uneven surface. Thus, tasks even vs even-ABC and uneven vs uneven-ABC showed significant differences for these gait variables.

Gait metrics smoothness and regularity are impacted by surface. Thus, tasks even vs uneven and even-ABC vs uneven-ABC showed significant differences for these gait variables. Pace (m/s), Variability (%), rhythmicity (steps/min), and regularity are affected strongly by cognitive task. Thus, tasks even vs even-ABC and uneven vs uneven-ABC showed significant differences for these gait variables.

The numerical values of gait parameters during all four tasks are detailed in **Supplementary Table 2.**

Association of gait quality with cognition

When adjusted for age, sex, education, and BMI, gait pace speed was not associated with any cognitive measures (**Table 3**). A lower stride time variability during even-ABC (ρ=-.31) and uneven-ABC (ρ= .28) was associated with better MMSE scores. Faster rhythmicity cadence and greater adaptability signal amplitude variability (standard deviation AP) was associated with better MMSE scores (ρ in range .22 to .28). Adaptability during even (ρ=.21) and uneven (ρ=.19) walk-only tasks was associated with Trails B. No associations of gait aspects such as similarity and smoothness with cognition were observed.

Table 3. Partial Spearman correlations of gait variables to cognition. **p<0.01, *p<0.05, ^p<0.1 for gait speed (covariates: age, sex, BMI, education), For all other gait variables (covariates: age, sex, BMI, education, gait speed in respective task). No association significant after Bonferroni correction 8x4x3 = 96, $p_{corrected}$ =.05/96 = .0005, CoV=Coefficient of Variation, AP=Anterior-Posterior, V=Vertical, ML=Mediolateral

	Mini-Mental State Exam				*Time taken to do Trail Making Test - A*				*Time taken to do Trail Making Test - B*			
Gait aspect and variable	**Even**	**Uneven**	**Even-ABC**	**Uneven-ABC**	**Even**	**Uneven**	**Even-ABC**	**Uneven-ABC**	**Even**	**Uneven**	**Even-ABC**	**Uneven-ABC**
Pace, Gait Speed	0.11	0.03	0.09	0.07	-0.07	-0.07	-0.02	-0.03	-0.17^	-0.17^	-0.12	-0.15
Variability, Stride time CoV	0.04	0.02	**-0.31****	**-0.28****	0.07	0.01	0.13	0.07	-0.07	-0.02	0.09	0.04
Rhythmicity, Cadence	**0.22***	**0.22***	**0.29****	**0.26****	-0.02	-0.06	-0.04	-0.07	-0.05	-0.15	-0.06	-0.02
Adaptability, Standard Deviation AP	**0.26****	**0.24***	**0.22***	0.18^	-0.17^	-0.16^	-0.16^	-0.10	**-0.21***	**-0.19***	-0.15^	-0.08
Similarity, Cross-correlation AP-V	0.03	0.04	0.11	0.09	-0.01	0.04	-0.11	-0.09	-0.03	-0.01	-0.02	-0.02
Smoothness, Harmonic Ratio AP	-0.04	-0.09	0.08	0.14	0	0.04	-0.09	0.03	0.10	0.05	0.04	0.01
Power, Peak Frequency V	0.13	0.13	0.05	0.18^	0	-0.04	-0.03	-0.05	0.04	0.03	0.11	0.02
Regularity, Entropy rate ML	-0.04	-0.02	-0.13	-0.12	0.07	0.06	0.10	-0.07	0.04	-0.03	0.03	-0.07

Discussion

Walking challenge of an uneven surface and the cognitive task independently affected gait quality metrics, with no significant interactions. While walking speed or pace, is an important aspect of gait changes with age [43], we found that other aspects of gait are important in understanding gait changes during challenged walking tasks. Specifically, gait variability and regularity increased, while smoothness and rhythmicity decreased due to uneven surface and alternate alphabeting tasks. Some gait metrics (variability, rhythmicity, and adaptability) were moderately associated with general cognitive functioning (MMSE scores).

The gait metrics of pace, variability, rhythmicity, and power monotonically changed as the walking tasks increased in difficulty (i.e., even, to uneven, even-ABC, and finally uneven-ABC) (refer Figure 1). Smoothness is a definite indicator of surface differences which is sensitive to external peripheral input ground reaction sensory input. The sensitivity of variability and rhythmicity metrics to cognitive tasks may illustrate the potential for cognitive task to restrict walking or even alter walking to a more step by step planned event task. Older adults may be matching walking pace to letter rhythm. Regularity may be a hallmark of the automaticity of walking, sensitive to both surface and cognitive changes and the variation in individual performance. Marked changes in these gait parameters were related to the cognitive alternate alphabeting task. Gait speed or pace is often an indicator of declines in function and increased fall risk [43]–[45]. In addition to the pace ~~speed~~, changes in gait performance during dual-task walking have shown to be related to an increased fall risk [31], [46]. A combination of gait parameters calculated from accelerometer can reflect the slow or fast walking pace. ~~Perhaps, adjustments in the acceleration deduced gait parameters underlie the slower or faster walking speed performance.~~ Thus, specific gait performance measures may provide insights on interventions improving overall walking efficiency and stability, beyond increasing gait speed [47].

In our analyses, gait pace speed during single as well as dual-tasks was not found to be associated with cognitive functioning, similar to the findings of another study [5]. Jayakody et al [11], also did not find associations of gait pace speed with the exception of processing speed and verbal fluency. One possible explanation is that our participants were somewhat highly educated and a comparatively high-functioning sample of older adults. The mean age and means for the Trails A and B tests indicate our sample executive cognitive functioning at or above the 80th percentile for similar aged older adults [48]. For this population, gait characteristics other than walking speed (e.g. adaptability) may be more sensitive to subtle changes of early, age-related cognitive decline. We found rhythmicity and adaptability during all walking tasks were associated with global cognition and to a lesser extent, executive functioning. The gait adaptability is mainly needed when navigating the environment and adapting the body to match the surface and ensure the ability to move forward, but is less about trying to make decisions on conflicting information (e.g., dual-tasking, additional cognitive task), this ability is clearly needed the executive function tested by Trails-B. Association of the MMSE scores with changes in variability and rhythmicity when performing a concurrent cognitive task while walking, imply that measures of general cognitive functioning can be sensitive to dual-task decline in gait performance. The association found between gait adaptability and Trails B, while small, may suggest that cognitive flexibility is important. Similarly, previous research in laboratory and daily-life walking have demonstrated greater acceleration (adaptability) and rhythmicity to be associated with better physical function, mobility, fatigability, and fitness [32], as well as to increased life-space [38]. We have defined adaptability as the standard deviation of signal acceleration amplitude. In other words, we quantify adaptability to represent spread of signal amplitude distributions. Adaptability can then be interpreted as the ability to shift between lower and higher variability as one navigates complex tasks. Gait adaptation could occur either as a response to mechanical perturbations or as a response to visual stimuli including walking on rough terrain, stepping over obstacles or making a turn [49]. Under the specific dual-task conditions, the measure of adaptability needs more investigation.

Gait quality metrics are altered from the baseline even walking condition when cognitive and physical challenges are presented. These changes are not large in a healthy older population but can be markers of change with age. Increasing the challenge during walking may increase these effects and bring out new relationships. For example, MacAulay, et al. used a more complex task of spelling a given five-letter word backwards, in which gait variability was associated with executive function and not global cognition [12]. Examining older adults with reduced cognitive functioning will also provide insights into the relationship between cognition and gait quality. Previous studies assessing gait during challenging tasks have shown reduced gait performance in individuals with poorer cognitive function and potentially at high risk of dementia [50]–[52], lending evidence that gait and cognition are complementary [53]. Further research is necessary to understand the impact of cognitive functioning on gait quality beyond walking pace ~~speed~~ and relationship with cognition. Our study with high-functioning older adults suggests that task-related changes in gait quality occur and they are related to subtle changes in cognitive functioning.

Limitations and future work

Our observational cross-sectional analyses is limited to uneven walking and alternate alphabeting task, selected to reflect physical and conversational cognitive demand needed for community mobility [11]. These tasks may not adequately represent challenges faced during day-to-day walking, particularly for high-functioning older adults, who may do substantial walking under varied conditions. Often obstacles, slopes and curve path are experienced in everyday walking, which may be accounted for while assessing gait in future studies. These challenging walking conditions may require more cognitive resources for judgement, motor planning, and navigation [54]. The choice of the concurrent cognitive task is also important and can impact gait differently [55], [56]. Future studies could explore this cognitive-physical interaction in gait using more targeted and challenging cognitive tasks during more challenging walking conditions.

We also limited our cognitive measures to MMSE and Trails tests. It may be possible that different domains of cognitive function such as recall, working memory, and verbal fluency may have a relation to dual-task gait [10], [11]. Thus, these cognitive domains should be examined further. Additionally, more targeted cognitive tests could be included. For example, Redfern and colleagues suggest that specific inhibitory measures, such as perceptual inhibition, may be related to postural control [57]. Others have suggested that visuospatial function is important for moving through space [58], [59]. Depression and anxiety may influence these relationships [60], so neuropsychological exams such as Geriatric Depression Score, anxiety, and fear of falling may also help in distinguishing performance under complex environments. We did not record the participants' perception of a task difficulty, nor did we ask them to prioritize gait over alphabeting. But the participants appear to have consistent alphabeting performance across all dual-tasks. This too may be an important factor and be a potential influence of whether the older person prioritized the cognitive task or walking for the cognitive condition. Future studies may be designed to explore this prioritization influence in dual-task conditions for walking.

Regarding measurement of changes during dual-task gait, this study used accelerometry signals. However, other modalities such as neuroimaging assessments from functional near-infrared spectroscopy are gaining popularity to examine cortical activation of frontal areas during walking [61]–[63]. Increased or reduced brain activation may help in assessment of shift in processing resources and presence of cognitive load during complex walking tasks. Besides, brain networks and connectivity could provide useful insights into brains' structural associations with mobility function and behavior [64], [65]. We are examining these modalities for our future work.

Conclusion

Physical and cognitive walking challenges affect gait quality. Global cognition and executive functioning, appear to be associated with changes in gait quality measures~~, specifically adaptability~~. While gait speed is reduced during uneven walking and dual-task walking, metrics of gait quality when exposed to challenge walking is potentially informative for identifying those most at risk for poor functional outcomes such as cognitive decline but needs more research.

Statement of Ethics

All study activities were reviewed and approved by the University of Pittsburgh Institutional Review Board, approval numbers STUDY19090074, STUDY19060190, and PRO14070560. Participants provided written informed consent prior to completion of study activities.

Conflict of Interest Statement

The authors have no conflict of interest to declare

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Author Contributions

Anisha Suri contributed to formulating research aims and methods for this study, processing gait accelerometry signals, performing statistical analysis, interpreting results, and writing the initial draft of the manuscript. Dr. Jessie VanSwearingen contributed to formulating research aims for this sudy, formulating the main study protocol and data collection procedures for Program to Improve Mobility in Aging (PRIMA) and the data collection procedures, interpreting results, and revising and editing the manuscript. Dr. Caterina Rosano contributed to formulating the main study protocol and data collection procedures for Move Monogahela-Youghiogheny Healthy Aging Team (MoveMYHAT) and revising and editing the manuscript. Dr. Jennifer S. Brach contributed to formulating main study protocol and data collection procedures for PRIMA, and in revising and editing the manuscript. Dr. Mark S. Redfern contributed to formulating research aims and statistical methods for this study, interpreting results, and revising and editing the manuscript. Dr. Ervin Sejdic contributed to formulating the research aims, processing gait accelerometry signals and revising and editing the manuscript. Dr. Andrea L. Rosso contributed to formulating the research aims and methods for this study, formulating the main study protocol and data collection procedures for PRIMA and Neural Mechanisms of Community Mobility (NMCM), interpreting the results, and revising and editing the manuscript.

Data Availability Statement

All enquiries about data access can be directed to the corresponding author.

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