Full length article

What features of the built environment matter most for mobility? Using wearable sensors to capture real-time outdoor environment demand on gait performance

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ABSTRACT

Background: A growing body of research has demonstrated relationships between built environment characteristics and outdoor mobility. However, most of this work has relied on composite scores of the built environment.

Research question: Which properties of the outdoor built environment are associated with the greatest change in gait metrics in a real-world setting?

Methods: 25 community-dwelling adults from Southeast Michigan were equipped with mobile inertial measurement units and walked a 1300-meter outdoor course with varying environmental demands. Environmental properties were documented in sections of the course using the Senior Walking Environmental Assessment Tool. Gait speed, left foot cadence, and stride length were used to identify the built environment properties under which mobility was most challenged using linear mixed models. We hypothesized that subjects would adapt to demanding environments by decreasing gait speed, increasing cadence, and shortening stride length.

Results: Properties of the built environment were significantly associated with changes in gait speed, left foot cadence, and stride length. Properties that were most important for predicting gait speed included slope, sidewalk condition, and presence of holes. Sidewalk slope, bumps, and the presence of a curb cut were all significant predictors of left foot cadence. Mean stride length of the outdoor course was significantly associated with the section's condition, slope, holes, bumps, width, and the presence of grooves and bumps at a curb.

Significance: Associations between environmental properties and gait parameters were differential across the three mobility outcomes. When examining which properties of the built environment are challenging to navigate it is important to understand the relative influence of specific properties on gait metrics. Knowledge of which built environment properties are barriers for walking behavior is critical for the design of inclusive sidewalks and streets.

1. Introduction

Mobility references movement in many forms and is critical for engagement in leisure activities and everyday tasks [1–5]. A large body of research has focused on understanding the individual and clinical determinants of mobility function [6–8]. A growing area of research has examined the environmental context in which mobility occurs [9–13]. Evidence indicates that older adults living in areas with environmental barriers, such as poor sidewalk conditions, are at greater risk of reporting mobility limitations [13,14]. On the other hand, residence in an area with environmental facilitators, such as curb cuts, have been shown to be positively associated with independent mobility [9,15].

While this research has been important in raising awareness of the role of the environment for mobility function, it has yet to identify which specific properties of the built environment have the greatest impact on mobility. Studies often use a composite measure of 'walkability' that combines multiple aspects of the environment into an overall index [9,16]. As a result, it is not possible to identify the specific effect of key environmental properties on mobility performance. Previous studies have typically relied on crude self-report measures of mobility difficulty, preventing an understanding of the specific dimensions of gait that are most affected by particular environmental properties. Certain spatial-temporal components of gait (i.e. speed, cadence, and stride length) may be more vulnerable to environmental challenges when producing an adaptive mobility response [17]. Slower walking speed, shorter step length and increased cadence are typical responsive strategies to enhance gait stability. Yet, there is a limited research that has identified which real-world environmental properties cause the greatest magnitude of change in gait metrics.

To date, the majority of research examining gait performance in response to environmental perturbations has taken place within a lab setting. For example, lab studies using a treadmill at various speeds found that gait stability is greater at slower compared to faster speeds [18,19]. Navigating obstacles in a virtual lab environment resulted in decreased walking speed and shorter step length [20]. Other lab studies have found that when exposed to balance perturbations, participants maintained their walking speed by increasing their cadence and decreasing their step length [21]. Namely, one study had examined the effects of slope on pedestrian gait speed, cadence and step length in an outdoor setting [22]. However, research on how these gait indicators respond to multiple real-world environmental demands needs further investigation in an outdoor setting.

The purpose of this study was to identify which properties of the outdoor built environment have the greatest impact on multiple dimensions of gait performance. Based on previous results from lab studies [18,19], we hypothesized that walking over challenging built environmental properties (e.g., uneven sidewalks, sidewalk barriers and steeper slopes) would result in slower gait speed, increased cadence, and shorter stride length [21].

2. Materials and methods

2.1. Participants

A convenience sample of 40 community-dwelling adults from Southeast Michigan gave written informed consent to participate in this study. Participants were recruited through online advertising and the posting of flyers at community centers, libraries, senior centers, and on a University campus. In order to maximize the diversity of subjects with respect to age and physical capacity, participants were also recruited from a senior housing facility. Exclusion criteria were age less than 18 years, not regularly walking outdoors, unable to read or speak English, or inability to participate due to significant physical or mental limitations. Data collection took place between June and September 2013. All study procedures were reviewed by the Institutional Review Board.

2.2. Standard laboratory measures

Prior to commencing the outdoor walking course, participants completed an assessment of comfortable gait speed (CGS) within a controlled indoor environment. CGS was assessed over a 6-meter distance using a standard stopwatch. CGS was used to assess participants underlying functional mobility capacity prior to walking the outdoor course [23]. Age was self-reported by study participants.

2.3. Walking route

Two outdoor walking routes at two complementary study sites were used to capture a range of built environment challenges. One site was located on a University campus (1,300-meter course) and a second site was located at the senior housing facility (250-meter course). The campus site had multiple intersecting two-lane streets and pedestrian walkways with designated cross walks where participants crossed the street. The senior housing site was on a busy 5-lane street with few trees. Built environment properties over each of the fixed walking routes were documented by a trained rater using the Senior Walking Environment Assessment Tool – Revised (SWEAT-R) [24]. The SWEAT-R is a 162-item tool which assesses the presence and quality of built environment characteristics important for walking. For this study, we focused on items assessing sidewalk condition (i.e. poor condition vs. moderate condition), slope of the sidewalk (i.e. flat vs. moderate slope), obstructions in the sidewalk (e.g. crack, hole, bump), sidewalk width (in meters), sidewalk material (e.g. concrete, brick), presence of a curb cut, and presence of grooves or bumps at the curb cut. The overall subjective rating of the condition of the sidewalk was measured by asking the auditor to rate the section as poor, moderate, or good. The auditor was instructed to rate the slope of the section as flat/gentle, moderate slope, or steep slope. This captured the grade of the slope, regardless of the slope direction (up or down). The walking routes were divided into homogenous sections with respect to environmental hazards, generating 12 unique sections across the two walking routes.

Two members of the study team accompanied each participant over the course to document timed splits for each section and serve as a spotter for safety. Participants were asked to refrain from speaking throughout the course and to limit conversation to requests for clarification only.

2.4. Gait assessment

Gait speed, cadence, and stride length were captured in real time over the walking courses using wearable IMUs (Opal, APDM Inc., Portland, OR, USA). The APDM IMU system has been shown to have good accuracy and repeatability in measuring spatiotemporal outcomes during ambulation [25–28]. The IMUs track movement in space and time using a combination of triaxial gyroscope, triaxial accelerometer, and triaxial magnetometer. Study participants were equipped with an IMU device attached to the top of their left foot to capture gait speed, cadence, and stride length. Movement data were captured on the device and then uploaded and processed later by proprietary software (Mobility Lab™), to calculate gait speed (meters per second), left foot cadence (number of left foot steps per minute), and left foot stride length (meters per left foot step).

Gait speed, defined as the forward speed of the participant, captures a participant's preferred speed when navigating the environment and is important for health, motor control, as well as fall risk [29]. Left foot cadence, defined as the number of steps made per minute, captures the frequency of steps when an individual is walking. Stride length, defined as the length in meters per step, captures the forward distance travelled by a foot during a gait cycle.

2.5. Statistical analysis

Gait metrics collected over the walking course are clustered within sidewalk sections (level 2) and within individuals (level 3). Therefore, we used multilevel linear mixed models to estimate the effects of individual and environmental factors on the three gait outcomes [30]. Linear mixed models consider the correlation of observations within persons and within segments, effectively comparing an individual's performance on one section to their performance on another section [30]. CGS and age were centered at their mean to assist in parameter interpretation. Separate models were conducted for each of the three kinematic outcomes (gait speed, stride length and cadence). For each gait metric, we first estimated the null model (overall mean). A second model included age and indoor CGS (at level 3) to account for

individual-level factors contribution to gait differences. A third model included environmental properties of the sidewalk sections (at level 2). For all models, random variance in gait metrics within sections and within persons was captured with a random intercept parameter at level 2 (section) and level 3 (person).

3. Results

Of the 40 participants, four did not report to the study site for their scheduled visit, three dropped out due to rain, one dropped out due to shortness of breath, and seven participants did not have valid IMU data for analysis. This resulted in 25 participants with complete mobility and environment data. Among the 25 participants, 20 participants (mean age 38.5) were observed walking over the university campus route while 5 participants (mean age 69) were observed walking over the senior housing facility route. Four of 25 participants reported using a mobility device, with 2 using a walker and 2 using a cane. In total, there were 5036 unique gait observations and 176 unique sections of the walking route among 25 participants. On average, there were 419.7 gait observations within each section of the course and 201.4 gait observations within each study participant.

Descriptive statistics for the 25 participants are presented in Table 1. On average participants were 44.6 years of age, ranging from 18 to 74 years of age. Mean CGS over all participants was 1.2 m per second, and 60% of participants were female. Across all sections in the walking course, 90% had cracks, 80% were made up of concrete or asphalt, and 70% had a curb cut at a street or driveway crossing. Sidewalk obstructions were common; across all sections 40% had a bump, 30% had holes, and 30% had grooves/bumps at curb cuts. The average width of all sidewalk sections was 2.5 m and 70% of the sections were rated as moderate (compared to good) condition. Moderate slopes were present in 8% of the sidewalk sections.

Table 1

Descriptive statistics of 25 community-dwelling adults from Southeast Michigan, characteristics of 176 unique sections of the walking route, and 5036 measurements of mobility.

	N	Mean/ Percentage	Standard Deviation
Level 3 (Individual)			
CGS (m/s)	25	1.2	0.3
Age	25	44.6	18.1
Female (%)	25	60.0	
Level 2 (Sidewalk Section)			
Moderate condition[a] (%)	176	70.0	
Moderate slope[b] (%)	176	8.0	
Sidewalk crack (%)	176	90.0	
Sidewalk hole (%)	176	30.0	
Sidewalk bump (%)	176	40.0	
Sidewalk width (m)	176	2.5	1.3
Sidewalk Material Concrete/ Asphalt[c] (%)	176	80.0	
Curb cut present (%)	176	70.0	
Grooves/ bumps at curb cut (%)	176	30.0	
Level 1 (Mobility Measure)			
Gait speed	5036	1.3	0.3
Left foot cadence	5036	56.0	5.9
Stride Length	5036	1.3	0.3

Note. CGS = Comfortable Gait Speed.
  [a] Sections of the route were rated as 'moderate' or 'good' sidewalk condition by the auditor; the proportion of sections rated as 'moderate' is displayed above.
  [b] Sections of the route were rated as 'flat/gentle' or 'moderate slope'; the proportion of sections rated as 'moderate slope' is displayed above.
  [c] compared to brick sidewalk material.

Table 2

Fixed Effects Estimates (Top Panel) and Variance Estimates (Bottom Panel) for Outdoor Gait Speed (meters/second).

Parameter	Model 1	Model 2	Model 3
	Fixed effects		
Intercept	1.30[*] (0.05)	1.31[*] (0.03)	1.34[*] (0.02)
Level 2 (sidewalk section)			
Moderate condition[a]			−0.07[*] (0.02)
Moderate slope[b]			−0.08[*] (0.03)
Sidewalk hole			0.05[*] (0.02)
Level 3 (person)			
CGS		0.59[*] (0.09)	0.58[*] (0.08)
Age		−0.006[*] (0.001)	−0.006[*] (0.001)
	Random parameters		
Level 2 (sidewalk section)			
ICC[c] (σ_{is}^2)	0.08	0.15	0.10
Level 3 (person)			
ICC[c] (σ_i^2)	0.73	0.46	0.49

Note. Standard errors are in parentheses.
[i] = individual participant; s = section of the route; CGS = Comfortable Gait Speed.
  [a] Sections of the route were rated as 'moderate' or 'good' sidewalk condition by the auditor; good condition is the reference group.
  [b] Sections of the route were rated as 'flat/gentle slope' or 'moderate slope'; 'flat/gentle slope' is the reference group.
  [c] Intraclass correlation coefficient (ICC) represents the proportion of total variance in gait that is present at the sidewalk level and the person level.
  [*] $p < .05$.

3.1. Gait speed

Average gait speed across all segments of the walking courses was 1.30 m/s (Table 2). For every one unit increase in age there was, on average, a 0.006 m per second decrease in gait speed. Among all environmental properties, only sidewalk condition, slope, and the presence of a hole in the sidewalk were significantly associated with outdoor gait speed (Table 2). Mean gait speed was 0.07 m/s slower while walking on sidewalks rated as moderate compared to good condition, given all other variables in the model (p < .001). A steeper slope was associated with a decline in gait speed (p = .009). However, the presence of holes on the sidewalk was associated with a 0.05 m/s increase in gait speed (p = .001). Within Model 1 7.5% of total variance is attributed to differences between sections, individual level parameters explained 36.8% of the variance at the person level (Model 2), and 31.8% of the variance present at the section level was explained by environmental properties (Model 3). However, significant variation in gait speed remained between persons and across segments, suggesting the role of other unmeasured individual and environmental factors for gait speed.

3.2. Left foot cadence

Estimated mean left foot cadence among participants was 56.3 steps per minute (Table 3). For every one unit increase in age there were, on average, 0.04 fewer left foot steps per minute. In terms of environmental factors, cadence increased in sections of the course with bumps, but decreased in sections with slopes or curb cuts (Table 3). Traversing a section of the route with bumps on the sidewalk was associated with an increase of 0.67 steps per minute compared to a section with no bumps (p = .007). Compared to sections without slopes, cadence decreased by 1.71 steps per minute when walking over sidewalk sections with a moderate slope (p = .004). Sidewalk sections that included a curb cut were associated with a reduction in the number of steps per minute by 0.25 (p = .05). Within Model 1, 4.2% of the variance is attributed to differences between sections (Table 3), individual level parameters explained 8.6% of the variance at the person level (Model

Table 3

Fixed Effects Estimates (Top Panel) and Variance Estimates (Bottom Panel) for Models of Left Foot Cadence (steps/minute).

Parameter	Model 1	Model 2	Model 3
	Fixed effects		
Intercept	56.3* (0.91)	56.52* (3.62)	56.50* (0.79)
Level 2 (sidewalk section)			
Moderate slope[a]			−1.71* (0.57)
Sidewalk bump			0.67* (0.23)
Curb cut			−0.25* (0.13)
Level 3 (person)			
CGS		7.89* (2.77)	7.73* (2.73)
Age		−0.04 (0.04)	−0.04 (0.04)
	Random parameters		
Level 2 (sidewalk section)			
ICC[b](σ_{is}^2)	0.04	0.05	0.04
Level 3 (person)			
ICC[b](σ_{i}^2)	0.61	0.55	0.55

Note. Standard errors are in parentheses.

i = individual participant; s = section of the route; CGS = Comfortable Gait Speed.

[a] Sections of the route were rated as 'flat/gentle slope' or 'moderate slope'; 'flat/gentle slope' is the reference group.

[b] Intraclass correlation coefficient (ICC) represents the proportion of total variance in gait that is present at the sidewalk level and the person level.

* p < .05.

2), and 14.8% of the variance present at the section level was explained by environmental properties (Model 3).

3.3. Stride length

Estimated left foot stride length across the walking courses was 1.38 m (Table 4). For every one unit increase in age there was, on average, a 0.002 m decrease in left foot stride length. Multiple

Table 4

Fixed Effects Estimates (Top panel) and Variance Estimates (Bottom panel) for Models of Left Foot Stride Length (meters/step).

Parameter	Model 1	Model 2	Model 3
	Fixed effects		
Intercept	1.38* (0.04)	1.39* (0.02)	1.09* (0.10)
Level 2 (sidewalk section)			
Moderate condition[a]			−0.49* (0.13)
Moderate slope[b]			0.31* (0.12)
Sidewalk hole			0.10* (0.03)
Sidewalk bump			0.34* (0.10)
Sidewalk width			0.18* (0.05)
Curb cut grooves /bumps			−0.59* (0.17)
Level 3 (person)			
CGS		0.44* (0.09)	0.32* (0.08)
Age		−0.006* (0.001)	−0.002 (0.002)
	Random parameters		
Level 2 (sidewalk section)			
ICC[c](σ_{is}^2)	0.06	0.10	0.09
Level 3 (person)			
ICC[c](σ_{i}^2)	0.68	0.45	0.39

Note. Standard errors are in parentheses.

i = individual participant; s = section of the route; CGS = Comfortable Gait Speed.

[a] Sections of the route were rated as 'moderate' or 'good' sidewalk condition by the auditor; good condition is the reference group.

[b] Sections of the route were rated as 'flat/gentle slope' or 'moderate slope'; 'flat/gentle slope' is the reference group.

[c] Intraclass correlation coefficient (ICC) represents the proportion of total variance in gait that is present at the sidewalk level and the person level.

* p < .05.

environmental properties were associated with stride length (Table 4). Stride length decreased by almost half a meter (0.49 m) when walking over sections of the course that were in moderate compared to good condition (p < .001), and decreased by an estimated 0.59 m over sections with curb cuts that had grooves or bumps (p = .002). Conversely, stride length increased over sections of the course with moderate slopes (p = .02), with holes (p = .001), and with bumps (p = .002). Stride length was also longer when walking over wider compared to narrow sections of sidewalks (p = .002). Within Model 1, 5.9% of the variance is attributed to differences between sections (Table 4), individual level parameters explained 33.6% of the variance at the person level (Model 2), and 9.5% of the variance present at the section level was explained by environmental properties (Model 3).

4. Discussion

Using wearable IMUs in a real-world outdoor setting, we sought to identify which properties of the gait cycle are most altered in response to specific built environment challenges. Only a handful of studies have looked at the impact of the outdoor environment on real world mobility [31,32]. We extend this line of research by examining changes in three key gait metrics to capture gait adaptations in response to outdoor built environment challenges.

We found that indoor CGS was a consistent predictor of outdoor gait performance. Additionally, a number of environmental properties were significantly associated with a gait response independent of CGS. Table 5 summarizes the impact of the seven environmental properties on gait metrics. As anticipated, walking over sidewalks in less than good condition resulted in decreased gait speed and shorter stride length. However, contrary to our expectations, sidewalk obstructions (e.g. holes, bumps) were associated with an increase in speed and stride length. One potential explanation may be that participants attempted to navigate environmental obstructions through the elongation of their stride. While previous work in the lab setting has found cadence to be maintained or increase in response to environmental demands [20,21,33], only sidewalk bumps were associated with increased cadence. In contrast, walking over sidewalk sections with slopes or with curb cuts resulted in reduced cadence. These results are consistent with findings from Freire Júnior et al. who found that cadence decreased when participants were asked to dual task [34]. While previous research has mixed findings regarding the association between increased motor demand and changes in cadence [20,21,33,34], the results of this study indicate preferred cadence is dependent on which environmental characteristic the participant is navigating. When encountering an obstruction (e.g. bump) people may increase cadence, thereby increasing stability, in preparation for navigating the obstruction safely. Using these data we are unable to determine where the obstacle is along each section of the walking route. Therefore, we are unable to deconstruct the preparatory phase where participants increase cadence, from the crossing phase where participants increase stride length. However, when overcoming a uniform environmental feature, participants decreased cadence which may be an adaptive response to slow down and move more cautiously through their environment. More research is needed to fully understand these complex relationships.

Sidewalks with slopes had effects on all three gait outcomes, resulting in decreased gait speed, slower cadence, and an increase in stride length. The association between slope and gait speed (β = −0.08) is in the same direction as the association between slope and cadence (β = -1.71). However, it is in the opposite direction as the association between slope and stride length (β = 0.31). This suggests that changes in gait speed among sections with a slope are driven by the large change in cadence. This aligns with previous findings among healthy participants, where slow gait speed and preferred gait speed were mediated more by a change in cadence rather than a change in step length [35]. However, our findings conflict with previous evidence that suggests with increasing slope there is a decrease in step length [22]. The

Table 5

Summary of sidewalk characteristics that were significantly associated with gait speed, cadence and stride length and the direction of association between each environmental feature and mobility outcome.

	Moderate Slope	Moderate Condition	Sidewalk Hole	Sidewalk Bump	Curb Cut	Sidewalk Width	Curb Cut Grooves/ Bumps
Gait Speed	↓	↓	↑				
Cadence	↓			↑	↓		
Stride Length	↑	↓	↑	↑		↑	↓

Note. The absence of an arrow indicates no significant association between the environmental feature and the mobility outcome, an arrow pointing up indicates a positive association between environmental feature and mobility outcome, an arrow pointing down indicates an inverse association between environmental feature and mobility outcome.

disagreement may be due to the differences in measurement of gait kinematics and slope variability. Future research should examine this relationship in a real-life setting utilizing IMU devices. In conclusion, when traversing a section with a moderate slope, participants within this sample took longer, fewer steps that resulted in a reduction in gait speed. These findings underscore the need to examine the individual contribution of kinematics such as cadence and stride length, and the resulting gait speed when understanding effects of the built environment.

Strengths of this study include the collection of multiple gait metrics in real time, the quantification of attributes of the outdoor environment, and the real-world application of research. Using IMU devices we observed differential effects of environmental attributes on gait parameters. Additionally, our goal was to understand how the built environment impacts gait in the real world. By bringing our lab outside we were able to uncover some of the real-world adaptations that people make to their gait in response to environmental stimuli. However, this study also has limitations. This was a small sample size which limited our ability to detect differences between groups. Additionally, the small sample size limited ability to investigate interactions between individual and the environmental characteristics. Lastly, body height and body weight were not measured as part of the research protocol. Future research should investigate the interaction between an individual's underlying functional ability and the demands of the environment.

4.1. Conclusion

Associations between environmental properties and gait parameters were not homogeneous across the three mobility outcomes. Therefore, it is important to understand the relative influence of specific built environment properties on gait metrics. Detailed knowledge of environmental properties that affect specific dimensions of gait are necessary for planning effective mobility interventions at the environment or person-level. This is especially important for the growing population of older adults with varying levels of gait performance, especially for complex walking tasks (e.g. navigating environmental barriers) that require attention, processing, and planning [36–38].

Conflict of Interest

None.

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