Using Mobile, Wearable, Technology to Understand the Role of Built Environment Demand for Outdoor Mobility

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Abstract
Walking outdoors requires navigating a complex environment. However, no studies have evaluated how environmental barriers affect outdoor mobility in real time. We assessed the impact of the built environment on outdoor mobility, using mobile, wearable inertial measurement units. Data come from a convenience sample of 23 community-dwelling adults in Southeast Michigan. Participants walked a defined outdoor route where gait metrics were captured over a real-world urban environment with varying challenges. Street segments were classified as high versus low environmental demand using the Senior Walking Environmental Assessment Tool. Participants ranged in age from 22 to 74 years (mean age of 47 years). Outdoor gait speed was 0.3 m/s slower, and gait variability almost doubled, over the high-versus low-demand environments (coefficient of variability = 10.6% vs. 5.6%, respectively). This is the first study to demonstrate the feasibility of using

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wearable motion sensors to gather real-time mobility data in response to outdoor environmental demand. Findings contribute to the understanding of outdoor mobility by quantifying how real-world environmental challenges influence mobility in real time.

**Keywords**
mobile technology, mobility, built environment, environmental demand

**Introduction**

Mobility, defined as an individual’s ability to move about effectively in his or her surroundings (Shumway-Cook et al., 2002, 2003), is fundamental to independence, quality of life, and regular physical activity (Hirvensalo, Rantanen, & Heikkinen, 2000; Rantakokko, Iwarsson, Hirvensalo, et al., 2010; Rantakokko, Iwarsson, Kauppinen, et al., 2010; Simonsick, Guralnik, Volpato, Balfour, & Fried, 2005). In fact, maintaining mobility is considered by the World Health Organization (WHO) to be the best guarantee of retaining independence with aging (WHO, 1998). However, outdoor mobility requires navigating a complex environment that diverts attention from walking to constantly changing conditions and obstacles, which can create challenges for mobility (Clarke, 2014; Clarke, Ailshire, Bader, Morenoff, & House, 2008; Clarke, Ailshire, & Lantz, 2009; Clarke, Ailshire, Nieuwenhuijsen et al., 2011, Clarke & Gallagher, 2013).

Multiple conceptual frameworks have emphasized the dynamic nature of mobility, including the complex interactions between individual factors and environmental demand (Lawton, 1982; Verbrugge & Jette, 1994; Webber, Porter, & Menec, 2010; WHO, 2001). In particular, characteristics of the built environment, such as the quality and presence of transportation systems, street grids (connectivity), green space, housing density, the mix of residential, and other forms of land use, have repeatedly been shown to be associated with mobility (Berke, Koepsell, Moudon, Hoskins, & Larson, 2007; Frank, Kerr, Rosenberg, & King, 2010; Frank, Schmid, Sallis, Chapman, & Saelens, 2005; King et al., 2000; King et al., 2011; Michael, Beard, Choi, Farquhar, & Carlson, 2006; Michael, Green, & Farquhar, 2006; Rodriguez, Evenson, Diez Roux, & Brines, 2009; Rosso, Auchincloss, & Michael, 2011; Saelens, Sallis, & Frank, 2003). Similarly, pedestrian-oriented designs (e.g., continuous, barrier-free sidewalks, four-way stop signals, and pedestrian amenities) have been shown to be positively associated with mobility (Addy et al., 2004; Fisher, Li, Michael, & Cleveland, 2004; Humpel, Owen, & Leslie, 2002; Patterson & Chapman, 2004) while
uneven sidewalks, curbs, and inadequate street lighting have been identified as posing challenges for mobility (Debnam, Harris, Morris, Parikh, & Shirey, 2002; Markham & Gilderbloom, 1998).

Environmental barriers can be especially problematic for individuals with underlying weakness in movement-related functions and balance. Uneven sidewalks and sidewalk obstacles (i.e., loose stones and other debris) have been indicated in the vast majority of outdoor falls among older adults (Berg et al., 1997; Li et al., 2006). Poor street conditions, heavy traffic, and excessive noise have been shown to be associated with the onset of mobility impairments in older adults (Balfour & Kaplan, 2002; Schootman et al., 2006).

However, these findings are associations only, and the evidence is based almost exclusively on linkages between individual mobility data (usually from surveys) and secondary sources of environmental data. No studies have explicitly demonstrated that the mobility of an individual is directly a function of the environment under his or her feet. Although older adults with lower extremity impairment have been shown to avoid walking on grassy or uneven terrain (Shumway-Cook et al., 2002, 2003), no studies have evaluated how people actually move over these outdoor environments in real time.

Slow gait speed and increased gait variability are key indicators of compromised mobility (Alexander & Goldberg, 2005; Cummings, Studenski, & Ferrucci, 2014; Hausdorff, Rios, & Edelberg, 2001; Studenski et al., 2011). In the lab setting, gait variability has been shown to increase when individuals engage in attention-diverting tasks (dual tasking, for example, walking while talking; Springer et al., 2006; Verghese et al., 2002). However, examining dual-task mobility in a lab setting does not reflect the complexity of real-world challenges that individuals must negotiate when navigating their physical surroundings.

Wearable sensor technology has now advanced to the point where gait metrics can be captured in real time as people move across different environments (Caldas, Mundt, Potthast, de Lima Neto, & Markert, 2017; Washabaugh, Kalyanaraman, Adamczyk, Claflin, & Krishnan, 2017). Wearable inertial measurement units (IMUs) are increasingly used for assessing gait characteristics (Maetzler, Domingos, Srulijes, Ferreira, & Bloem, 2013). Compared with other types of noninvasive sensors used to assess gait (e.g., video motion analysis or gait mat), IMUs are unobtrusive and light, making them ideal for ambulatory measurements in real-world outdoor environments (Del Din, Godfrey, Mazzà, Lord, & Rochester, 2016; Vienne, Barrois, Bufflat, Ricard, & Vidal, 2017). IMUs consist of built-in gyroscopes, accelerometers, and magnetometers and use adaptive algorithms to generate different kinematic gait parameters in real time (Caldas et al., 2017).
IMUs show great promise for studying outdoor mobility because they are relatively inexpensive, measure gait metrics for an unlimited number of steps in real time, and can be used to examine gait and movement in real-world settings (Washabaugh et al., 2017). In comparison with surveys, retrospective reports, and daily diaries, data from wearable sensors can capture real-time mobility responses to environmental demand and are not subject to recall or other sources of bias (Maetzler et al., 2013).

In this study, we used gait speed and gait variability captured from wearable IMUs to objectively examine the impact of outdoor environmental demand on mobility. We hypothesized that walking in outdoor settings with higher environmental demand would lead to reduced gait speed and increased gait variability compared with walking across outdoor settings with lower environmental demand.

**Method**

**Participants**

Data come from a convenience sample of 40 community-dwelling adults residing in Southeast Michigan. Participants were recruited through flyers posted at locations throughout Ann Arbor, Michigan, including at community centers, libraries, senior centers, and on campus at the University of Michigan (UM). To maximize the diversity of subjects with respect to age and physical capacity, participants were also recruited from a senior housing facility. Inclusion criteria included 18 years of age or older and ability to walk safely outdoors (with personal or equipment assistance if needed).

**Study Procedure**

Data collection took place between June and September 2013 at two complementary study sites designed to capture a range of built environment challenges. One site was located on the UM central campus and a second site was located at a senior housing facility. The UM site had multiple intersecting two-lane streets and pedestrian walkways with designated crosswalks. The senior housing site was on a busy five-lane street with few trees.

Preliminary assessments were first conducted indoors to assess gait speed and dual-task capacity in a controlled environment. Participants were then equipped with matchbox-sized mobile inertial measurement units (IMU) devices (Ambulatory Parkinson’s Disease Monitoring; www.apdm.com) on their shoes and asked to walk a defined outdoor course (250 m at the senior housing facility; 1,300 m on UM campus) along surrounding...
streets and sidewalks that included common elements of the outdoor built environment (e.g., sidewalks, pedestrian crossings, curbs, walkways). The IMU devices used in this study contained a built-in accelerometer, gyroscope, and magnetometer, allowing for the real-time capture of gait measurements on a 3D plane.

Two members of the study team accompanied each participant over the course, one documenting timed splits with a stopwatch at predefined points while the other acted as a spotter for safety. Participants were instructed to refrain from talking during the outdoor course and to limit conversation to requests for clarification only. Participants received US$30 as a token of appreciation for their participation. All study procedures were reviewed by the UM’s Institutional Review Board and informed consent was obtained from all study participants.

**Individual Measures**

Gait variability was assessed in the outdoor course using stride length variability (SLV). Gait variability was not measured in the indoor tests. Stride length, defined as the distance between consecutive heel strikes of the same foot, was obtained in real time using the IMUs. Variability was measured using the coefficient of variation, expressed as a percentage (standard deviation / mean ×100).

Gait speed in meters per second was captured in real time over the outdoor course using the mobile IMUs. We also accounted for gait speed in the controlled indoor setting to assess mobility capacity in the absence of environmental demand. Participants were first instructed to walk a 6-m indoor course at a comfortable pace. Participants then walked the same 6-m distance, turned without stopping, and returned to the starting point (total distance = 12 m). The test was then repeated with a cognitive demand component (dual task), where participants completed the same 12-m walk while reciting alternate letters of the alphabet (i.e., a, c, e, g, . . ., etc.; Verghese et al., 2002). The dual-task cost is defined as the arithmetic difference in time for the 12-m walk with and without the cognitive task, divided by the time without cognitive task.

Additional sociodemographic and health characteristics were obtained from a self-completed questionnaire, including gender, age (in years), and marital status (dichotomized as married vs. not married for analyses). Annual household income was dichotomized as greater than or equal to US$40,000 versus less than US$40,000 for analyses. An index of the number of medically diagnosed chronic conditions was created to capture multimorbidity (range = 0-6 conditions).
Measures of Environmental Demand

The Senior Walking Environmental Assessment Tool–Revised (SWEAT-R) was used to characterize the built environment over the outdoor walking courses. The SWEAT-R is an environmental audit instrument with demonstrated interrater reliability that is specifically designed to capture features in the built environment that are relevant for older adult mobility (Michael, Beard, et al., 2006; Michael et al., 2009). At each study site, consecutive 5-m sections of the walking course were assessed by a trained rater based on the presence of specific physical characteristics, including sidewalk material, sidewalk width (in feet and inches), presence of obstructions (e.g., cracks, bumps, parking meters), any slope, traffic lanes, as well as information on curb height, curb cuts, and quality of pedestrian crossings.

Following Michael and colleagues (Chaudhury, Mahmood, Michael, Campo, & Hay, 2012; Michael et al., 2009), we classified each 5-m section according to the level of built environmental demand (high vs. low) for mobility based on standardized items in the SWEAT-R. Sections of the course that were characterized as high demand totaled 351 m and were composed of asphalt and concrete. The overall condition of the sidewalks in the high-demand sections was rated as fair/good but several sidewalk obstructions were present. Specifically, 90% of the 5-m sections were observed to have cracks, 50% had poles and signs, and over 30% had holes. There were four crosswalks in the high-demand sections of the course that were intended for pedestrian use, but they did not have traffic signals, yield signs, or pedestrian signals, with the exception of one stop sign and one pedestrian crossing sign. Only one of the pedestrian crossings included broad apron curb cuts.

Although the street and sidewalk sections in the course surrounding the senior housing site were classified entirely as high environmental demand, the course on the UM campus contained both high- and low-demand environments. The low environmental demand course sections totaled 123 m, where the overall sidewalk condition was evaluated as fair/good and no major sidewalk obstructions were recorded, with the exception of some weeds/leaves and a bump on two of the segments.

Statistical Analysis

Multivariable linear regression was used to model the relationship between built environment demand and the two gait metrics (outdoor gait speed and SLV). Models were conducted in sequence to first examine the adjusted relationships between demographic/health factors and gait metrics. Subsequent models adjusted for mobility capacity (indoor 6-m gait speed, centered at the
mean for analyses) and dual-task cost. The final model added the indicator variable for built environment demand. Generalized estimating equations (GEEs) were used to account for the correlation between observations for the same person when observed across both high- and low-demand environments. All models were estimated in SAS 9.4 and statistical significance was assessed with a two-tailed alpha of .05.

Results

Of the 40 subjects recruited for the study, 30 were enrolled at the UM site and 10 were enrolled at the senior housing site. Of the 40 enrolled subjects, four (10%) did not report to the study site for their scheduled visit. Of the 36 remaining participants, four (10%) did not complete the walking course due to rain (three at UM site) or shortness of breath (one at the senior housing site). An additional nine (23%) participants did not have valid IMU data for analysis due to a data recording failure. All analyses presented are based on 23 participants with valid IMU data—17 at the UM site and six at the senior housing site.

Descriptive characteristics of the 23 study participants in the analytic sample are presented in Table 1. Participants ranged in age from 22 to 74 years with a mean age of 47 years. Six individuals (26%) were over the age of 65. Just over half (56.5%) of the study participants were female. Fourteen of 23 participants reported an annual household income of less than US$40,000 per year, and eight were married. On average, participants had 0.7 (±1.4) chronic health conditions (Table 1). Four participants from the senior housing site used an assistive device for mobility (cane, walker).

Average indoor gait speed was 1.17 m/s, which is within a standard range considered normal among middle-aged and older adults (Brach, Berthold, Craik, VanSwearingen, & Newman, 2001; Okoro et al., 2006; Studenski et al., 2003). When adding a turn over the longer 12-m distance in the Walk-Turn-Walk test, gait speed dropped to 0.98 m/s on average. Overall, gait speed was 0.2 m/s slower when adding the cognitive challenge, resulting in a 22% reduction in speed (dual-task cost for cognitive challenge).

Mean gait speed outdoors was slightly faster than indoor gait speed (1.38 vs. 1.17 m/s, respectively, Table 1), but outdoor gait speed was 0.3 m/s slower over the high- versus low-demand environments (1.25 vs. 1.57 m/s, respectively). Expressing this difference as a ratio of low-demand speed indicates that walking over high-demand environments results in a 20% reduction in gait speed (outdoor dual-task cost). On average, SLV over the outdoor course was 8.5%, but gait variability almost doubled over the high-demand environments (coefficient of variability [CV] = 10.6% vs. 5.6% in high- vs. low-demand environments, respectively).
Tables 2 and 3 report the regression coefficients and 95% confidence intervals for the multivariable linear regressions for outdoor gait speed and SLV, respectively. A greater number of chronic health conditions was associated with slower outdoor gait speed (Model 1, Table 2), while higher income was associated with less variability in stride length (Model 1, Table 3), even after controlling for other demographic factors.

* $p < .05$. ** $p < .0001$. Models 2 and 3 add mobility capacity (indoor gait speed) and dual-task cost. Net of the demographic and health factors, indoor gait speed, and dual-task cost were not significantly associated with SLV outdoors (Table 3). But mobility capacity indoors was related to outdoor gait speed; for each 0.1 m/s increase in indoor gait speed, gait speed outdoors was .057 m/s faster (Model 2, Table 2).

### Table 1. Descriptive Statistics for Analytic Sample ($N = 23$).

<table>
<thead>
<tr>
<th>Category</th>
<th>$M$ (±SD) or %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>46.74 (18.78)</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>43.48</td>
</tr>
<tr>
<td>Female</td>
<td>56.52</td>
</tr>
<tr>
<td>Marital status</td>
<td></td>
</tr>
<tr>
<td>Married</td>
<td>34.78</td>
</tr>
<tr>
<td>Not married</td>
<td>65.22</td>
</tr>
<tr>
<td>Household income</td>
<td></td>
</tr>
<tr>
<td>&lt;US$40,000 per year</td>
<td>60.87</td>
</tr>
<tr>
<td>US$40,000 or more per year</td>
<td>34.78</td>
</tr>
<tr>
<td>Missing/refused</td>
<td>4.35</td>
</tr>
<tr>
<td>Number of chronic health conditions</td>
<td>0.73 (1.40)</td>
</tr>
<tr>
<td>Indoor gait speed (m/s)</td>
<td></td>
</tr>
<tr>
<td>Single task (6 m)</td>
<td>1.17 (0.30)</td>
</tr>
<tr>
<td>Single task (12 m with turn)</td>
<td>0.98 (0.20)</td>
</tr>
<tr>
<td>Dual task</td>
<td>0.78 (0.27)</td>
</tr>
<tr>
<td>Dual task for cognitive challenge</td>
<td>0.22 (0.22)</td>
</tr>
<tr>
<td>Outdoor gait speed (m/s)</td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>1.38 (0.30)</td>
</tr>
<tr>
<td>Over high-demand environments</td>
<td>1.25 (0.27)</td>
</tr>
<tr>
<td>Over low-demand environments</td>
<td>1.57 (0.26)</td>
</tr>
<tr>
<td>Outdoor gait variability (%)</td>
<td></td>
</tr>
<tr>
<td>Stride length CV—overall</td>
<td>8.49 (5.17)</td>
</tr>
<tr>
<td>Over high-demand environments</td>
<td>10.62 (5.60)</td>
</tr>
<tr>
<td>Over low-demand environments</td>
<td>5.61 (2.59)</td>
</tr>
</tbody>
</table>

*Note. CV = coefficient of variability is defined as the ratio of the standard deviation to the mean in the right foot, expressed as a percentage.
Table 2. Regressing Gait Speed on Outdoor Built Environment Demand (Unstandardized Regression Coefficients) \( (N = 23)\).

<table>
<thead>
<tr>
<th>Demographic and health factors</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.56*** (1.38, 1.74)</td>
<td>1.67*** (1.49, 1.86)</td>
<td>1.67*** (1.48, 1.86)</td>
<td>1.78** (1.61, 1.95)</td>
</tr>
<tr>
<td>Demographic and health factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>−0.01 (−0.01, 0.01)</td>
<td>−0.01 (−0.01, 0.01)</td>
<td>−0.01 (−0.01, 0.01)</td>
<td>−0.01 (−0.01, 0.01)</td>
</tr>
<tr>
<td>Female(^a)</td>
<td>−0.13 (0.31, 0.05)</td>
<td>0.08 (−0.14, 0.31)</td>
<td>0.09 (−0.14, 0.31)</td>
<td>0.10 (−0.12, 0.31)</td>
</tr>
<tr>
<td>Number of chronic conditions</td>
<td>−0.12*** (−0.19, −0.06)</td>
<td>−0.06* (−0.13, −0.01)</td>
<td>−0.07 (−0.15, 0.01)</td>
<td>−0.05 (−0.13, 0.03)</td>
</tr>
<tr>
<td>Income (\geq)US$40,000(^b)</td>
<td>−0.08 (−0.20, 0.05)</td>
<td>−0.09 (−0.19, 0.01)</td>
<td>−0.09* (−0.18, −0.01)</td>
<td>−0.08 (−0.18, 0.01)</td>
</tr>
<tr>
<td>Married(^c)</td>
<td>0.05 (−0.11, 0.22)</td>
<td>0.03 (−0.10, 0.16)</td>
<td>0.03 (−0.11, 0.17)</td>
<td>0.02 (−0.11, 0.15)</td>
</tr>
<tr>
<td>Mobility capacity and dual-task cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor gait speed (m/s)</td>
<td>0.57*** (0.24, 0.90)</td>
<td>0.57*** (0.25, 0.89)</td>
<td>0.60*** (0.27, 0.91)</td>
<td></td>
</tr>
<tr>
<td>Dual-task cost</td>
<td>0.01 (−0.47, 0.50)</td>
<td>0.08 (−0.40, 0.55)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Built environment demand</td>
<td></td>
<td></td>
<td>−0.23*** (−0.33, −0.12)</td>
<td></td>
</tr>
</tbody>
</table>

Note. 95% confidence intervals are indicated in parentheses under parameter estimates.\(^a\)Reference group is male. 
\(^b\)Reference group is income <US$40,000 per year. 
\(^c\)Reference group is not married (separated/divorced, widowed, never married). 
\(^d\)Reference group is low environmental demand. 
\(^*p < .05. **p < .01. ***p < .0001.\)
Table 3. Regressing Stride Length Variability (CV %) on Outdoor Built Environment Demand (Unstandardized Regression Coefficients) (N = 23).

<table>
<thead>
<tr>
<th></th>
<th>Demographic and health factors</th>
<th>+ Mobility capacity</th>
<th>+ Dual-task cost</th>
<th>+ Built environment demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
<td>Model 3</td>
<td>Model 4</td>
</tr>
<tr>
<td>Intercept</td>
<td>8.94*** (4.62, 13.27)</td>
<td>9.22*** (3.81, 14.64)</td>
<td>10.13*** (4.29, 15.98)</td>
<td>8.48** (3.17, 13.79)</td>
</tr>
<tr>
<td>Demographic and health factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>−0.01 (−0.11, 0.09)</td>
<td>−0.02 (−0.18, 0.14)</td>
<td>−0.01 (−0.16, 0.14)</td>
<td>−0.02 (−0.17, 0.14)</td>
</tr>
<tr>
<td>Female*</td>
<td>−1.45 (−4.72, 1.81)</td>
<td>−1.04 (−4.96, 2.89)</td>
<td>−1.01 (−5.24, 3.23)</td>
<td>−1.30 (−5.74, 3.14)</td>
</tr>
<tr>
<td>Number of chronic conditions</td>
<td>1.16 (−0.27, 2.59)</td>
<td>1.29 (−0.58, 3.16)</td>
<td>2.38 (−0.48, 5.23)</td>
<td>2.30 (−0.38, 4.99)</td>
</tr>
<tr>
<td>Income $\geq$US$40,000^b$</td>
<td>−2.67* (−5.59, −0.24)</td>
<td>−2.65* (−5.51, −0.20)</td>
<td>−2.22 (−5.01, 0.57)</td>
<td>−1.99 (−4.87, 0.89)</td>
</tr>
<tr>
<td>Married^c</td>
<td>1.71 (−2.02, 5.44)</td>
<td>1.68 (−1.97, 5.32)</td>
<td>0.71 (−2.16, 3.57)</td>
<td>0.85 (−1.94, 3.63)</td>
</tr>
<tr>
<td>Mobility capacity and dual-task cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor gait speed (m/s)</td>
<td>1.09 (−5.22, 7.40)</td>
<td>0.28 (−5.84, 6.41)</td>
<td>−0.34 (−6.67, 5.99)</td>
<td>−10.75 (−24.31, 2.81)</td>
</tr>
<tr>
<td>Dual-task cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Built environment demand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High environmental demand^d</td>
<td></td>
<td>4.33*** (2.28, 6.38)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. 95% confidence intervals are indicated in parentheses under parameter estimates. CV = coefficient of variation of stride length in the right foot expressed as a percentage.

*Reference group is male.

^Reference group is income <US$40,000 per year.

^Reference group is not married (separated/divorced, widowed, never married).

^Reference group is low environmental demand.

*p < .05. **p < .01 ***p < .001.
For both gait metrics, mobility was compromised over the high-demand environments. Net of indoor mobility capacity and health/sociodemographic factors, study participants walked 0.23 m/s slower over the high-demand compared with low-demand environments ($p < .001$, Model 4, Table 2). Similarly, adjusting for demographic and health factors, as well as indoor gait speed and dual-task cost, SLV was over 4% greater over the more challenging built environment segments (e.g., uneven sidewalks, sidewalk obstacles; $p < .001$, Model 4, Table 3). We also assessed whether the effect of environmental demand on outdoor gait metrics varied by respondent age (continuous), but these interaction effects were not statistically significant.

**Discussion**

This is the first study to demonstrate the feasibility of using wearable motion sensors to gather real-time mobility data in response to outdoor environmental demand. Quantifying gait measurement using wearable IMUs holds great promise for continuous, unobtrusive, and objective mobility assessments in real-world environments (Maetzler et al., 2013). Research and development with IMUs are occurring quickly, and improvements in gait detection algorithms and software synchronization (Vienne et al., 2017) will facilitate greater use of this technology in future work on the environment and outdoor mobility.

Although previous research has examined how gait patterns change in lab versus real-world settings (Bock & Beurskens, 2010), this is the first study to empirically test the impact of environmental demand for outdoor mobility. As hypothesized, we found that walking in outdoor settings with higher environmental demand resulted in reduced gait speed and more variable gait responses than walking across low-demand environments. Outdoor gait speed was reduced by 20% over high-demand environments and gait variability almost doubled in high- compared with low-demand environments. The outdoor gait speed cost of navigating high-demand environments was almost equivalent to the indoor dual-task cost with the cognitive challenge, suggesting that walking outdoors requires multiple attention-diverting tasks consistent with a cognitive challenge. This finding is consistent with previous studies showing that executive function and walking speed are task dependent, and complex walking tasks that require greater sensorimotor adaptation result in higher dual-task cost (Coppin et al., 2006), particularly among older adults (Ble et al., 2005).

Gait speed outdoors was somewhat faster than indoor gait speed on average, potentially as a result of acceleration over the longer distance in the outdoor course. Although indoor gait speed was positively associated with
outdoor gait speed, it was not related to outdoor gait variability. Thus, gait variability in response to environmental demand is not a function of mobility capacity (indoor gait speed), suggesting that gait variability may be an adaptive response to environmental demand. Too much or too little variability in gait has been associated with greater fall risk in those with normal gait speed (Brach, Berlin, VanSwearingen, Newman, & Studenski, 2005). Further research is needed to understand the extent to which gait variability in response to environmental demand is a positive or negative adjustment.

The ability to maintain independent mobility in the face of declining health and function is a dynamic process that includes interpersonal, social, and environmental resources highlighting the importance of the person–environment fit (Lawton, 1982). We found no variation in the effects of the environment on gait across individual factors, including age, and at different levels of physical or cognitive capacity. An individual’s capacity to adapt his or her gait to specific environmental challenges is likely a key factor shaping mobility difficulty. Further research with larger samples is needed to understand the extent to which real-time gait adaptation in response to environmental demand captures mobility difficulty across individuals with different levels of capacity.

Despite the strengths of this study, there are important limitations. Due to the small number of subjects in this pilot study, results are preliminary, and replication is needed with a larger sample. Due to unexpected weather changes and technology limitations in real-time IMU processing, gait metrics were not generated for all participants in the study. However, these conditions were random (not related to individual characteristics) and the gait metrics from excluded participants are unlikely to be systematically different from those who had complete IMU data. Although environmental demand was captured using a well-validated measure (Michael et al., 2009), we were unable to directly identify which environmental feature(s) (i.e., uneven sidewalk, pothole, etc.) within each street segment influenced gait. In addition, we acknowledge that the SWEAT-R was not designed to capture dynamic pedestrian and traffic patterns, which could impact the level of environmental demand in our study and introduce unmeasured confounding. Future studies should consider using the SWEAT-R in combination with other auditing tools to measure smaller segments and live traffic and pedestrian patterns to better understand the direct influence of specific environmental features on gait metrics.

In spite of these limitations, our results confirm that what researchers have been finding in observational and lab studies is true in the real world: Outdoor mobility does indeed change in the face of outdoor environmental challenge. This is a first step toward a better understanding of the relationship between...
outdoor mobility and real-world environmental challenges. These findings have important implications for understanding how gait adaptations in a real-world setting could be used to enhance mobility and reduce fall risk. Such information is critical for clinicians and service providers to make informed decisions about the risks and benefits of engaging in outdoor mobility. In addition, these results can inform urban planning about priorities for the design of community infrastructure. Ultimately, a greater understanding of the dynamics between individual factors and environmental demand will promote long-term, healthy, aging in place.

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