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# Built environment correlates of objectively-measured sedentary behaviours in densely-populated areas

Mohammad Javad Koohsari [a,b,c,*], Ai Shibata [d], Kaori Ishii [a], Sayaka Kurosawa [e], Akitomo Yasunaga [f], Tomoya Hanibuchi [g], Tomoki Nakaya [g], Suzanne Mavoa [c], Gavin R. McCormack [h,i,j,a], Koichiro Oka [a]

[a] Faculty of Sport Sciences, Waseda University, Japan
[b] Behavioural Epidemiology Laboratory, Baker Heart and Diabetes Institute, Australia
[c] Melbourne School of Population and Global Health, The University of Melbourne, Australia
[d] Faculty of Health and Sport Sciences, University of Tsukuba, Japan
[e] Graduate School of Sport Sciences, Waseda University, Japan
[f] Faculty of Liberal Arts and Sciences, Bunka Gakuen University, Japan
[g] Graduate School of Environmental Studies, Tohoku University, Japan
[h] Department of Community Health Sciences, Cumming School of Medicine, University of Calgary, Canada
[i] Faculty of Kinesiology, University of Calgary, Canada
[j] School of Architecture, Planning and Landscape, University of Calgary, Canada

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## ABSTRACT

Few studies examine associations between objectively-calculated neighbourhood built environment attributes and objectively-assessed sedentary behaviour in different geographical locations, especially in highly-populated environments. Additionally, no study, to our knowledge, has investigated associations between objective measures of neighbourhood built environment attributes and objectively-assessed sedentary behaviours in middle-aged adults, despite the fact that this is a critical stage of life when age-related functional decline begins. We examined the associations between neighbourhood built environment attributes with the total, and patterns of, objectively-assessed sedentary behaviours in a densely-populated area in Asia. Data from 866 adults (ages 40 to 64) living in Japan were included. Four classifications of sedentary behaviours, including daily total sedentary time, duration and number of long (≥30 min) sedentary bouts and breaks per sedentary hour, were estimated using hip-worn accelerometers. Individual (population density, availability of destinations, number of intersections, and distance to the nearest park) and composite (walkability and Walk Score®) neighbourhood built environment indices were calculated using geographic information systems. Covariate-adjusted multilevel linear mixed effects models were used to estimate the associations between the neighbourhood built environment attributes and sedentary behaviours. Population density and availability of destinations were positively associated with sedentary behaviours; however, the number of intersections was negatively associated with sedentary behaviours. No associations were observed between the distance to the nearest park and sedentary behaviours. There were positive associations between walkability and total sedentary time, and duration and the number of long sedentary bouts. Walk Score® was positively associated with total sedentary time and the number of long sedentary bouts. These findings suggest that urban design attributes supportive of walking (except for the number of intersections) may encourage sedentary behaviour among middle-aged adults living in densely-populated environments.

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* Corresponding author. 2-579-15 Mikajima, Tokorozawa, Saitama 359-1192 Japan.

*E-mail addresses:* javadkoohsari@aoni.waseda.jp (M.J. Koohsari), Shibata.ai.ga@u.tsukuba.ac.jp (A. Shibata), ishiikaori@waseda.jp (K. Ishii), sayakakurosawa@akane.waseda.jp (S. Kurosawa), yasunaga@bunka.ac.jp (A. Yasunaga), hanibuchi@gmail.com (T. Hanibuchi), tomoki.nakaya.c8@tohoku.ac.jp (T. Nakaya), suzanne.mavoa@unimelb.edu.au (S. Mavoa), Gavin.McCormack@ucalgary.ca (G.R. McCormack), koka@waseda.jp (K. Oka).

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## 1. Introduction

There is accumulating evidence that sedentary behaviour may have deleterious health effects, regardless of physical activity level (Bailey et al., 2019; Ekelund et al., 2016). Sedentary behaviour refers to “any waking behaviour characterised by an energy expenditure $\leq$1.5 metabolic equivalents (METs) while in a sitting or reclining posture” (Tremblay et al., 2017). A national cohort study in the United States of America (US) found that total and prolonged uninterrupted sedentary time was associated with a higher risk of all-cause mortality among middle-aged and older adults, independent of physical activity level (Diaz et al., 2017). A meta-analysis of prospective cohort studies found that adults’ daily sedentary time was associated with increased risks of colorectal cancer (Ma et al., 2017). Nevertheless, adults spend most of their waking hours in sedentary behaviours such as TV viewing, car driving, and sitting during work. For example, a study of US adults found a daily average of 8.4 h of accelerometer-assessed sedentary time (Healy et al., 2011b). In Japan, older adults spend an average of 8.8 h per day in accelerometer-assessed sedentary time (Shibata et al., 2018).

Multiple levels of influences, including individual, social, and urban design factors, need to be taken into account in order to reduce habitual sitting behaviours (Owen et al., 2011). In particular, the ‘neighbourhood built environment’ is receiving increased attention, mainly because environmental factors can bring about widespread and sustainable population-level changes in behaviour patterns (Chokshi and Farley, 2014). The fundamental assumption when focusing on the built environment is that people’s choice to engage in sedentary behaviour may depend on facilitators and barriers in their neighbourhood. Several systematic reviews have provided preliminary evidence on the associations between various neighbourhood built environment attributes and sedentary behaviours (Koohsari et al., 2015b; Müller et al., 2020; O’donoghue et al., 2016; Prince et al., 2017). For example, a systematic review found that adults residents who lived in urban areas were less likely to be sedentary compared with those who lived in rural areas (Koohsari et al., 2015b). Availability of green spaces, neighbourhood environment walkability, and safety were also found as correlates of adults’ sitting time (O’donoghue et al., 2016).

Although this evidence is promising, current knowledge on the associations between neighbourhood built environment attributes and sedentary behaviours is limited in several important ways. First, the majority of previous studies were conducted in Western countries. Notably, there are few studies conducted in Asian, densely-populated, areas that examined associations between the objectively-calculated built environment attributes and objectively-assessed sedentary behaviours. According to a recent systematic review on the correlates of sedentary behaviours in Asia, most of the previous studies relied on self-reported measures of the built environment and sedentary behaviour, which are subject to recall bias (Müller et al., 2020). Additionally, previous studies examining neighbourhood built environment correlates of sedentary behaviour have overlooked the pattern of sedentary behaviour such as the frequency or length of sedentary bouts and breaks. The adverse health effects of sedentary behaviour are not only due to the total duration of sitting time but also the patterns of sedentary behaviour such as sedentary bouts and breaks (Credeur et al., 2019; Dempsey et al., 2018). Furthermore, no study, to our knowledge, has investigated associations between objective measures of neighbourhood built environment and objectively-assessed sedentary behaviours in middle-aged adults (i.e., aged 40–64 years), despite the fact that this is a critical stage of life when age-related functional decline starts to occur (World Health Organization, 2002).

Therefore, this study examined the associations of the neighbourhood built environment attributes with the total, and patterns of, objectively-assessed sedentary behaviours in a sample of middle-aged adults. Our participants were living in two densely populated Japanese urban localities with population densities higher than those of many Western cities.

## 2. Methods

### 2.1. Data source and participants

This study is a sub-study of a larger project conducted at Waseda University, which aimed to explore personal, social, and urban design correlates of active and sedentary behaviours in Japanese adults. Detailed methods of study design and recruitment of the larger project have been documented elsewhere (Ishii et al., 2018). Briefly, a random sample of adults (aged 40–64 years) was selected from residents living in two Japanese urban localities, Koto Ward and Matsuyama City, with a population density of 12,170 and 1,190 persons per km$^2$, respectively. An invitation letter was sent to 6,000 residents, randomly selected from the government registry of residential addresses from July to December 2013 and April 2014 to February 2015. A reminder letter was sent to non-respondents two weeks after the initial mailing. A total number of 866 individuals (response rate = 14.4%) agreed to participate in the study. A self-administered questionnaire and an accelerometer (with a log diary) were mailed to each participant. A book voucher (¥1000, equivalent to about US$10) was given to those participants who completed the study (n = 779). All participants provided written informed consent. The study was approved by the Research Ethics Committee, Waseda University, Japan (2012–269).

### 2.2. Measures

*Sedentary behaviours.* A validated tri-axial accelerometer (Active style Pro model HJA-350IT; Omron Healthcare, Kyoto, Japan) was used to objectively-assess sedentary behaviour (Ohkawara et al., 2011; Oshima et al., 2010). Participants were instructed to wear the accelerometer on their waist for at least seven consecutive days, except when sleeping or during water-based activities. Non-wear time was defined as intervals of at least 60 consecutive minutes of no activity (0.9 or less METs) (Ohkawara et al., 2011), with allowance for up to two minutes of observations of some limited movement ($\leq$1.0 METs) within these periods (Healy et al., 2011a). Those who wore the accelerometer for $\geq$4 days (including one non-working day), $\geq$10 h/day of wear time were included in this study (Healy et al., 2011b). Sedentary behaviour was defined with an estimated accelerometer intensity of $\leq$1.5 METs (Ainsworth et al., 2011; Tremblay et al., 2017). Four sedentary behaviour outcomes were estimated: daily total sedentary time, duration and number of long ($\geq$30 min) sedentary bouts, and breaks per sedentary hour. The total sedentary time per day was calculated by summing the time spent engaged in any sedentary behaviour (Tremblay et al., 2017). Sedentary bouts referred to periods of uninterrupted sedentary time and a prolonged sedentary bout was defined as at least 30 consecutive minutes of sedentary time (Thorp et al., 2012; Tremblay et al., 2017). A sedentary break was identified as a non-sedentary bout in between two sedentary bouts (Tremblay et al., 2017).

*Individual neighbourhood built environment attributes.* Four neighbourhood built environment attributes - population density, availability of destinations, number of intersections, and distance to the nearest park - were calculated by geographic information systems (GIS) (ArcGIS 10.1 software from ESRI). These attributes have been found to be associated with physical activities (McCormack and Shiell, 2011; Sugiyama et al., 2012), which may also be relevant to sedentary behaviours (Koohsari et al., 2020b). Two network-based buffers of 800 m (half a mile) and 1600 m (one mile) around participants’ geocoded residences were used to calculate population density, availability of destinations, and the number of intersections. These buffers were selected to be consistent with previous studies examining active and sedentary behaviours among adults (Koohsari et al., 2020b; Troped et al., 2014). Population density referred to the residential density of each buffer area excluding water and non-residential land. The source was the Half Grid Square of population census 2010 (approximately 500 m by 500 m grid cell). Nine types of public and private destinations were calculated within each buffer: banks, bookstores, convenience stores, elementary schools, community centres, post offices, restaurants, supermarket/department stores, and sports/fitness clubs. The spatial location of public destinations was obtained from the 2010–2013 National Land Numerical Information by the Ministry of Land, Infrastructure, Transport and Tourism (http://nlftp.mlit.go.jp/ksj-e/index.html). Private destinations were geocoded from the 2015 digitised version of Hello Page, which is a telephone directory maintained by Nippon Telegraph and Telephone Corporation. The total number of 3-way or more intersections were calculated within each buffer by using data from the 2015 Digital Maps (Basic Geospatial Information), which include GIS vector datasets created and updated by the Geospatial Information Authority of Japan (https://www.gsi.go.jp/common/000078705.pdf). Distance to the nearest park was calculated using data from the 2010 National Land Numerical Information by the Ministry of Land, Infrastructure, Transport and Tourism (http://nlftp.mlit.go.jp/ksj-e/index.html).

*Composite neighbourhood built environment indices.* Three composite neighbourhood built environment indices - walkability within 800 m and 1600 m of home, and Walk Score® - were included in this study. Similar to other studies (Adams et al., 2014; Hajna et al., 2016), walkability was calculated by summing the z-scores of population density, availability of destinations, and number of intersections within each buffer. Walk Score® calculates the walkability of any address based on access to a variety of destinations and street connectivity around that address (Hall and Ram, 2018). Its concurrent validity with walkable neighbourhood built environment attributes in Japan has been reported in detail elsewhere (Koohsari et al., 2018b). In brief, Koohsari et al. (2018b) found that there were significant positive associations between Walk Score® and objectively-calculated walkable built environment attributes in Japanese neighbourhoods. Notably, they found that Walk Score® was most closely associated with objectively-calculated intersection density and availability of local destinations (Koohsari et al., 2018b). In the current study, Walk Scores® were obtained by having two independent project members enter each participant's residential address into the Walk Score® publicly available interface (www.walkscore.com). Agreement between the Walk Score® values extracted by two members was checked by the first author.

*Covariates.* Participants self-reported their age, gender (female or male), working status (employed or unemployed), highest education (tertiary or below tertiary), marital status (single or couple), living status (alone or with others), and gross annual household income ($<$¥5,000,000 or $\geq$ ¥5,000,000). A national Japanese index of neighbourhood deprivation with census variables was used as an indicator of area-level socioeconomic status (Nakaya et al., 2014). The index was calculated using the 2010 population census of Japan. Accelerometer daily wear time was also included as a covariate. These covariates were initially chosen because of their associations with sedentary behaviours in the literature (Müller et al., 2020; O'donoghue et al., 2016; Prince et al., 2017).

### 2.3. Statistical analysis

Multilevel linear mixed effects models were used to estimate associations of neighbourhood built environment attributes with objectively-assessed sedentary behaviours. The models include a dichotomous area variable (=0 for Koto Ward and = 1 for Matsuyama City) as a covariate representing locality effects at the city level and a random effect term accounting for the possible clustering tendency of participants within neighbourhoods. Normality assumptions were checked by the QQ plots of the residuals. A three-step exploratory analysis was conducted to select relevant covariates in each model (Asiamah et al., 2020; Rezai et al., 2009). First, univariate models of the association between each dependent variable and each covariate were performed. Covariates with a $p \leq 0.25$ were kept for the next step. Second, regression models with the independent variables, plus each of the covariates selected through step 1, were conducted. We kept covariates that led to at least a 10% absolute change in any one of the coefficients of the independent variables. Finally, we ran the models using the covariates remaining from the previous step. For all point estimates, their 95% confidence intervals (95% CIs) were estimated. To enable comparison across variables, each neighbourhood built environment attribute (population density, availability of destinations, the number of intersections, and distance to the nearest park) was standardised (i.e., z-scores) prior to the regression analysis. Since multicollinearity was not detected — the variance inflation factor $<5$ (O'Brien, 2007) —, three individual neighbourhood built environment attributes in each buffer (population density, availability of destinations, and the number of intersections) were included in the same model. Furthermore, participants who were unable to engage in physical activity (n = 12) and those with invalid or missing accelerometer data (n = 68) were removed from the analysis. A complete-case analysis was chosen because the proportion of missing data for our variables of interest was low (5%) (Jakobsen et al., 2014, 2017). Analyses were conducted using Stata 15.0 (Stata Corp, College Station, Texas), and the level of significance was set at $p < 0.05$.

## 3. Results

Data from 674 participants were analysed, excluding those with missing variables (n = 25) (Fig. 1). Table 1 shows the characteristics of the study sample. About 61% in the sample were female (n = 414), about 82% were employed (n = 554), about 64% had a high tertiary educational attainment (n = 428), about 80% were in a couple (n = 540), about 89% lived with others (n = 602), and approximately 55% had an annual gross household income lower than ¥5,000,000 per year (n = 368). Table 2 shows the mean scores for participants' neighbourhood built environment attributes. There were significant ($p < 0.05$) Pearson's correlations between walkability within the 800 m and 1600 m buffers (r = 0.82), walkability within the 800 m buffer and Walk Score® (r = 0.59), and walkability within the 1600 m buffer and Walk Score® (r = 0.57).

Table 3 shows the results of the associations between neighbourhood built environment attributes with objectively-assessed sedentary behaviours. Adjusting for covariates, population density within the 800 m and 1600 m buffers was positively associated with total sedentary time, duration of long sedentary bouts, number of long sedentary bouts, and negatively associated with the number of sedentary breaks. Availability of destinations within the 800 m buffer was positively associated with duration of long sedentary bouts. Availability of destinations within the 1600 m buffer was also positively associated with duration of long sedentary bouts and number of long sedentary bouts, and negatively associated with the number of sedentary breaks. The number of intersections within the 800 m buffer was negatively associated with duration of long sedentary bouts and positively associated with the number of sedentary breaks. The number of intersections within the 1600 m buffer was negatively associated with total sedentary time and duration of long sedentary bouts and positively associated with the number of sedentary breaks. No significant associations were observed between the distance to the nearest park and sedentary behaviours. Walkability within the 800 m and 1600 m buffers were positively associated with total sedentary time ($\beta = 6.32$, 95% CI 1.86, 10.79; $\beta = 5.56$, 95% CI 1.25, 9.87), duration of long sedentary bouts ($\beta = 3.75$, 95% CI 0.13, 7.36; $\beta = 3.58$, 95% CI 0.19, 6.97), and the number of long sedentary bouts ($\beta = 0.07$, 95% CI 0.01, 0.13; $\beta = 0.08$, 95% CI 0.02, 0.14). No significant associations were observed between walkability within the 800 m and 1600 m buffers and the number of sedentary breaks. Walk Score® was positively associated with total sedentary time ($\beta = 0.62$, 95% CI 0.20, 1.04) and the number of long sedentary bouts ($\beta = 0.01$, 95% CI 0.00, 0.01). No significant associations were observed between Walk Score® and duration of long sedentary bouts and the number of sedentary breaks.

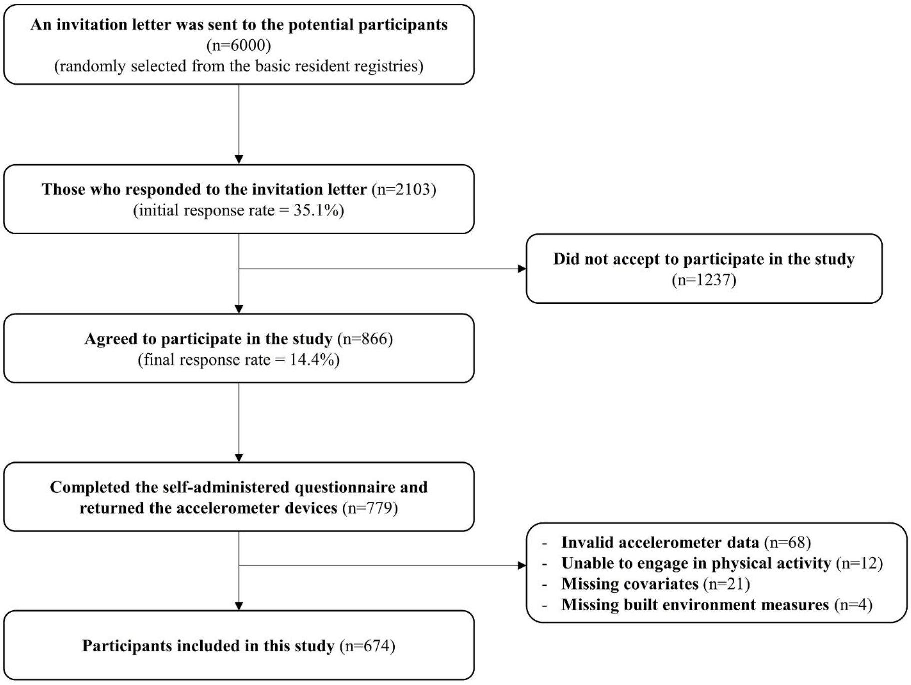

**Fig. 1.** Flow diagram of participants in the study.

**Table 1**
Characteristics of study participants (N = 674).

| Variable | Mean (SD) or N (%) |
|---|---|
| Age (years) | 52.2 (7.1) |
| Gender | |
| *Female* | 414 (61.4) |
| *Male* | 260 (38.6) |
| Working status | |
| *Employed* | 554 (82.2) |
| *Unemployed* | 120 (17.8) |
| Highest education | |
| *Tertiary* | 428 (63.5) |
| *Below tertiary* | 246 (36.5) |
| Marital status | |
| *Single* | 134 (19.9) |
| *Couple* | 540 (80.1) |
| Living status | |
| *Alone* | 72 (10.7) |
| *With others* | 602 (89.3) |
| Gross annual household income | |
| *< ¥5,000,000* | 368 (54.6) |
| *≥ ¥5,000,000* | 306 (45.4) |
| Accelerometer wearing days | 7.0 (0.9) |
| Accelerometer wear time (min/day) | 922.4 (90.8) |
| Total sedentary time (min/day) | 500.3 (121.2) |
| Duration of long (≥30 min) sedentary bouts (min) | 172.7 (95.7) |
| Number of long (≥30 min) sedentary bouts (times/day) | 3.3 (1.6) |
| Sedentary breaks (times/sedentary hour) | 9.3 (2.8) |

**Table 2**
Participants' neighbourhood built environment attributes (n = 674).

| | Mean | Median | SD |
|---|---|---|---|
| Population density | | | |
| *within 800m buffer* | 2458.90 | 323.16 | 3084.30 |
| *within 1600m buffer* | 2273.76 | 263.37 | 2856.37 |
| Availability of destinations | | | |
| *within 800m buffer* | 90.32 | 41.00 | 132.59 |
| *within 1600m buffer* | 395.66 | 197.00 | 435.92 |
| Number of intersections | | | |
| *within 800m buffer* | 444.11 | 477.50 | 204.32 |
| *within 1600m buffer* | 1610.99 | 1697.50 | 715.31 |
| Distance to the nearest park | 491.07 | 368.79 | 647.87 |
| Walkability | | | |
| *within 800m buffer* | 0.00 | 0.15 | 2.03 |
| *within 1600m buffer* | 0.00 | 0.12 | 2.13 |
| Walk Score® | 72.90 | 81.00 | 25.08 |

## 4. Discussion

We examined associations of neighbourhood built environment attributes with objectively-assessed sedentary behaviours among a sample of middle-aged adults in Japan. We found that neighbourhood walkability and Walk Score® were positively associated with several sedentary behaviour measures: those residents who lived in more walkable environments spent more time in sitting behaviours and had a greater number of long sedentary bouts. Among the individual neighbourhood built environment attributes, population density and availability of destinations were also positively associated with sedentary behaviours. The number of intersections showed inverse associations with sedentary behaviours.

Our findings are mostly consistent with previous studies conducted in compact European environments, which found that higher neighbourhood walkability had no associations or was associated with higher sedentary behaviour (Compernolle et al., 2017; Luijkx and Helbich, 2019; Van Dyck et al., 2010). For instance, a Belgian study found that living in a more walkable neighbourhood was associated with about 3% more accelerometer-based sedentary time (Van Dyck et al., 2010). A study conducted in the Netherlands found no significant associations between neighbourhood walkability and self-reported sedentary behaviour (Luijkx and Helbich, 2019). These findings are in contrast with previous evidence mainly from low-density urban areas in Western

**Table 3**
Association between neighbourhood built environment attributes with objectively-assessed sedentary behaviours (n = 674).

| | Total sedentary time (min/day) | | Duration of long (≥30 min) sedentary bouts (min) | | Number of long (≥30 min) sedentary bouts (times/day) | | Number of sedentary breaks (times/sedentary bout) | |
|---|---|---|---|---|---|---|---|---|
| | β (95% CI) | Standard error | β (95% CI) | Standard error | β (95% CI) | Standard error | β (95% CI) | Standard error |
| **Individual neighbourhood built environment attributes** | | | | | | | | |
| Population density | | | | | | | | |
| *within 800m buffer* | 31.24 (15.45, 47.02)*,[a] | 8.05 | 22.88 (9.70, 36.05)*,[b] | 6.72 | 0.37 (0.15, 0.60)*,[b] | 0.11 | −0.56 (−0.94, −0.18)*,[c] | 0.19 |
| *within 1600m buffe* | 35.42 (19.07, 51.76)*,[d] | 8.34 | 25.16 (11.02, 39.29)*,[e] | 7.21 | 0.38 (0.14, 0.62)*,[f] | 0.12 | −0.58 (−0.98, −0.17)*,[g] | 0.21 |
| Availability of destinations | | | | | | | | |
| *within 800m buffer* | 4.49 (−4.85, 13.84)[a] | 4.77 | 8.00 (0.19, 15.80)*,[b] | 3.98 | 0.10 (−0.03, 0.23)[b] | 0.07 | −0.22 (−0.44, 0.01)[c] | 0.11 |
| *within 1600m buffer* | 10.09 (−0.73, 20.90)[d] | 5.52 | 10.69 (1.35, 20.03)*,[e] | 4.77 | 0.16 (0.01, 0.32)*,[f] | 0.08 | −0.29 (−0.56, −0.02)*,[g] | 0.14 |
| Number of intersections | | | | | | | | |
| *within 800m buffer* | −8.61 (−19.20, 1.98)[a] | 5.40 | −10.03 (−18.87, −1.20)*,[b] | 4.51 | −0.12 (−0.27, 0.03)[b] | 0.08 | 0.30 (0.04, 0.55)*,[c] | 0.13 |
| *within 1600m buffer* | −13.69 (−25.64, −1.74)*,[d] | 6.10 | −13.23 (−23.58, −2.87)*,[e] | 5.28 | −0.16 (−0.34, 0.01)[f] | 0.09 | 0.34 (0.04, 0.64)*,[g] | 0.15 |
| Distance to the nearest park | −3.22 (−12.62, 6.17)[h] | 4.79 | −2.42 (−10.01, 5.17)[h] | 3.87 | −0.04 (−0.17, 0.09)[h] | 0.06 | 0.03 (−0.19, 0.25)[h] | 0.11 |
| **Composite neighbourhood built environment indices** | | | | | | | | |
| Walkability | | | | | | | | |
| *within 800m buffer* | 6.32 (1.86, 10.79)*,[i] | 2.28 | 3.75 (0.13, 7.36)*,[j] | 1.84 | 0.07 (0.01, 0.13)*,[k] | 0.03 | −0.08 (−0.18, 0.02)[l] | 0.05 |
| *within 1600m buffer* | 5.56 (1.25, 9.87)*,[m] | 2.20 | 3.58 (0.19, 6.97)*,[n] | 1.73 | 0.08 (0.02, 0.14)*,[o] | 0.03 | −0.10 (−0.20, 0.00)[p] | 0.05 |
| Walk Score® | 0.62 (0.20, 1.04)*,[i] | 0.21 | 0.30 (−0.04, 0.64)[q] | 0.17 | 0.01 (0.00, 0.01)*,[o] | 0.00 | −0.01 (−0.02, 0.00)[r] | 0.01 |

Note: β = unstandardized regression coefficients, CI = confidence interval. Individual neighbourhood built environment attributes were standardised (i.e., z-scores) prior to the regression analysis. Population density, availability of destinations, and the number of intersections in each buffer were included in the same model. Significant $p < 0.05$.

[a] Adjusted for age, educational attainment, marital status, income, living status, locality, neighbourhood socioeconomic status, and accelerometer daily wearing time.

[b] Adjusted for gender, educational attainment, marital status, income, living status, locality, and neighbourhood socioeconomic status.

[c] Adjusted for gender, educational attainment, marital status, income, living status, employment status, locality, neighbourhood socioeconomic status, and accelerometer daily wearing time.

[d] Adjusted for age, gender, educational attainment, marital status, income, living status, locality, neighbourhood socioeconomic status, and accelerometer daily wearing time.

[e] Adjusted for gender, marital status, income, living status, locality, and neighbourhood socioeconomic status.

[f] Adjusted for gender, educational attainment, marital status, income, living status, locality, neighbourhood socioeconomic status, and accelerometer daily wearing time.

[g] Adjusted for gender, marital status, income, living status, employment status, locality, neighbourhood socioeconomic status, and accelerometer daily wearing time.

[h] Adjusted for educational attainment, locality, and neighbourhood socioeconomic status.

[i] Adjusted for educational attainment, income, locality, and neighbourhood socioeconomic status.

[j] Adjusted for educational attainment, marital status, income, locality, and neighbourhood socioeconomic status.

[k] Adjusted for educational attainment, marital status, locality, and neighbourhood socioeconomic status.

[l] Adjusted for educational attainment, marital status, living status, locality, and neighbourhood socioeconomic status.

[m] Adjusted for educational attainment.

[n] Adjusted for educational attainment, marital status, and locality.

[o] Adjusted for educational attainment and locality.

[p] Adjusted for educational attainment, marital status, living status, and locality.

[q] Adjusted for educational attainment, income, and locality.

[r] Adjusted for educational attainment, marital status, income, living status, and locality.

countries such as Australia, Canada, New Zealand, and the US, where better neighbourhood walkability has been associated with less sedentary behaviour (Hinckson et al., 2017; Koohsari et al., 2014, 2020b; Kozo et al., 2012; McCormack and Mardinger, 2015). For example, a study conducted in the US found that neighbourhood walkability was associated with less self-reported car driving and TV viewing time (Kozo et al., 2012). In New Zealand, a study found that the availability of retail destinations and better street connectivity were associated with less accelerometer-assessed sedentary time (Hinckson et al., 2017). Another study conducted in Canada found that walkable environmental attributes were negatively associated with two typical adults' self-reported sedentary behaviours, including screen time and car driving (Koohsari et al., 2020b). Our findings extend previous research by testing associations between the neighbourhood built environment and objectively-assessed total, and bouts of, sedentary behaviours in a less explored densely-populated Asian environment.

There are some potential explanations for the observed positive associations between walkable neighbourhood built environment attributes and sedentary behaviours in our study. First, several environmental attributes of Japanese cities are at extreme levels compared with Western environments (Koohsari et al., 2018a). For example, the average population densities within 800 m and 1600 m in our study were more than 2000 person/km$^2$, which is higher than those in many previous studies and locations (Adams et al., 2014). Specific environmental attributes may be beneficial for sedentary behaviours up to a certain threshold, above which the positive effects of the built environment on these behaviours may disappear or become negative (Koohsari et al., 2018a). These indicate that the effects of neighbourhood built environment on sedentary behaviours may vary significantly depending on different geographical locations with different built environment characteristics. Future studies in highly dense areas are needed to explore how extreme levels of environmental attributes may influence sedentary behaviours. Second, it is likely that white-collar Japanese workers tend to live in more walkable areas mainly around public transportation stations compared with living in regional remote neighbourhoods. These workers tend to accumulate a high proportion of sedentary behaviours at work, since Japan has among the world's longest working hours (Ono, 2018). Further longitudinal studies are required to test whether the observed associations between neighbourhood walkability and sedentary behaviours remain unchanged when accounting for the self-selection issue (i.e., residents with a more sedentary lifestyle tend to live in high walkable areas).

Similar to some previous studies (Van Dyck et al., 2010; Veitch et al., 2016), our findings showed no significant associations between distance to the nearest park and sedentary behaviours. A potential reason for this finding may be the limitations of using a single measure of park availability. As discussed by Koohsari et al. (2015a), objective measures of park availability (i.e., distance to the nearest park) ignore the quality of parks. A single measure of distance to the nearest park also does not detect the possibility of having several parks around participants' residence (Kaczynski et al., 2014). For instance, Veitch et al. (2016) found that having more parks near home was associated with lower daily TV viewing time among women (a typical sedentary behaviour). Additionally, the effects of distance to the nearest park on a behaviour like sedentary time may start after a threshold distance (Kaczynski et al., 2009). The average distance to the nearest park in our study was about 500 m. This relatively limited range may be one reason for the lack of association between distance to the nearest park and sedentary behaviours in our sample.

Furthermore, one of the individual built environment attributes in this study, the number of intersections, was found to be negatively associated with sedentary behaviours. The number of intersections partly represents how connected streets are within a layout. More connected street layouts are likely supportive of active behaviours by providing shorter and more direct routes between destinations (Dill, 2004; Koohsari et al., 2017). Notably, the finding on the association between the number of intersections is in contrast with the composite indices of built environment attributes. One explanation for this finding is that built environment attributes co-exist and may act together in influencing health behaviours (Koohsari et al., 2020a). Therefore, the effects of this individual built environment attribute on sedentary behaviour may not always be similar to the effects of composite built environment indices like walkability. Further research is needed to explore the effects of a more comprehensive list of individual and composite built environment measures on sedentary behaviours.

There are some limitations in this study. This study was cross-sectional, and we cannot draw causal relationships between our variables. We used the best available data to calculate the neighbourhood built environment attributes. However, because not all the built environment data were annually updated, there was a temporal mismatch between our built environment and sedentary behaviour variables. It is likely that some changes in the built environment attributes in our study locations occurred between collecting sedentary behaviours and calculating built environment attributes. Since periodical GIS data are unavailable for our study locations, we are unable to elaborate on the magnitude of the built environment changes. Two spatial buffer sizes were employed to aggregate neighbourhood built environment attributes. Future studies can use a variety of buffer sizes in conceptualising the neighbourhood built environment to which participants are exposed (Mavoa et al., 2019). Moreover, accelerometer devices are unable to provide contextual information on the specific types of sedentary behaviours, and most devices cannot accurately detect upper or lower body movements.

This study benefits from several strengths. This was the first study, to our knowledge, that examined associations between objective neighbourhood built environment attributes and sedentary behaviours among middle-aged adults. We also objectively assessed sedentary behaviours using accelerometers. Furthermore, our inclusion of total, as well as patterns of, sedentary behaviours is novel.

## 5. Conclusions

The current study adds to the limited, but growing, literature in urban design and public health that seeks to identify correlates of sedentary behaviour as an emerging health risk factor. Focusing on objectively-calculated neighbourhood built environment attributes and objectively-assessed sedentary time and patterns in a less explored, densely-populated environment, our findings suggest that living in walkable environments may not be beneficial for middle-aged adults' sedentary behaviours. Moreover, by considering both individual and composite built environment measures, this study shed light on the ways built environment attributes may act together in influencing sedentary behaviours. More evidence is needed to explore how the neighbourhood built environment may influence sedentary behaviours in different geographical contexts.

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