早稲田大学審査学位論文

博士（スポーツ科学）

Activity-Friendly Built Environment and Cardiovascular Disease

アクティビティに配慮した建築環境と心血管疾患

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早稲田大学大学院スポーツ科学研究科

クサリ モハマドジャバッド

KOOHSARI, Mohammad Javad

研究指導教員: 岡 浩一朗 教授

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Preface

Author's declaration

This thesis comprises eleven peer-reviewed articles published in scientific journals with the collaboration of my co-authors. I am the first author of all of these papers. Below is the list of these papers:

1. **Koohsari, M. J.**, Oka, K., Nakaya, T., Vena, J., Williamson, T., Quan, H., & McCormack, G. R. (2023). Urban design and cardio-metabolic risk factors. *Preventive Medicine*, 173, 107552.

2. **Koohsari, M. J.**, & Oka, K. (2023). Walk Score® and space syntax in research on activity-friendly built environment and cardiovascular diseases. *Sport Sciences Research*. 20: 27-38.

3. **Koohsari, M. J.**, Nakaya, T., McCormack, G. R., & Oka, K. (2021). Socioeconomic disparity in cardiovascular health: The role of where we live. *Environmental Research Letters*. *16*: 041001.

4. **Koohsari, M. J.**, McCormack, G. R., Shibata, A., Ishii, K., Yasunaga, A., Nakaya, T., & Oka, K. (2021). The relationship between Walk Score® and perceived walkability in ultrahigh density areas. *Preventive Medicine Reports*. *23*: 101393.

5. **Koohsari, M. J.**, Shibata, A., Ishii, K., Kurosawa, S., Yasunaga, A., Hanibuchi, T., Nakaya, T., Mavoa, S., McCormack, G. R., & Oka, K. (2020). Built environment

correlates of objectively-measured sedentary behaviours in densely-populated areas. *Health & Place*. *66*: 102447.

6. **<u>Koohsari, M. J.</u>**, McCormack, G. R., Nakaya, T., & Oka, K. (2020). Neighbourhood built environment and cardiovascular disease: Knowledge and future directions. *Nature Reviews Cardiology*. *17*(5): 261-263.
7. **<u>Koohsari, M. J.</u>**, Oka, K., Nakaya, T., Shibata, A., Ishii, K., Yasunaga, A., & McCormack, G. R. (2020). Environmental attributes and sedentary behaviours among Canadian adults. *Environmental Research Communications*. *2*(5): 051002.
8. **<u>Koohsari, M. J.</u>**, Oka, K., Owen, N., & Sugiyama, T. (2019). Natural movement: A space syntax theory linking urban form and function with walking for transport. *Health & Place*. *58*: 102072.
9. **<u>Koohsari, M. J.</u>**, Sugiyama, T., Shibata, A., Ishii, K., Hanibuchi, T., Liao, Y., Owen, N., & Oka, K. (2018). Walk Score® and Japanese adults' physically-active and sedentary behaviors. *Cities*. *74*: 151-155.
10. **<u>Koohsari, M. J.</u>**, Sugiyama, T., Hanibuchi, T., Shibata, A., Ishii, K., Liao, Y., & Oka, K. (2018). Validity of Walk Score® as a measure of neighborhood walkability in Japan. *Preventive Medicine Reports*. *9*: 114-117.
11. **<u>Koohsari, M. J.</u>**, Sugiyama, T., Shibata, A., Ishii, K., Liao, Y., Hanibuchi, T., Owen, N., & Oka, K. (2017). Associations of street layout with walking and sedentary behaviors in an urban and a rural area of Japan. *Health & Place*. *45*: 64-69.

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Chapter 1. Introduction

This chapter explains the statement of the problem and the aims of this PhD research. It also describes the significance of this research and briefly provides an overview of the chapters of this thesis.

1.1. Cardiovascular disease, biomarkers, and risk factors

Cardiovascular disease remains the number one cause of death worldwide and is responsible for an estimated 17.9 million deaths each year (31% of all deaths globally) (World Health Organization, 2017a). They are “a group of disorders of the heart and blood vessels”, such as coronary heart disease and cerebrovascular disease (World Health Organization, 2017a). There are many biomarkers (such as blood pressure and lipid profile) and that are associated with cardiovascular disease. A biological biomarker is defined as “a characteristic that is objectively measured and evaluated as an indicator of normal biological processes, pathogenic processes, or pharmacological responses to a therapeutic intervention” (Vasan, 2006).

There are several risk factors for cardiovascular disease which can be categorised into modifiable and non-modifiable risk factors. Age, gender, and ethnicity can be listed as non-modifiable risk factors for cardiovascular disease. There are several behavioural risk factors for cardiovascular diseases, including physical inactivity, smoking, unhealthy diet, and smoking which can be modified to influence cardiovascular disease biomarkers (World Health Organization, 2017a). These behavioural risk factors can be modified to prevent or reduce the risk of clinical cardiovascular biomarkers.

1.2. Statement of problem

Cardiovascular disease is the number one cause of death in the world, responsible for about 17.9 million deaths per year (31% of all deaths worldwide) (World Health Organization, 2017a). There has been a decline in cardiovascular disease burden over the last two decades (Vos et al., 2020). However, cardiovascular disease remains to be among the top leading cause of non-communicable disease problems and death. Several modifiable risk factors, such as obesity, physical inactivity, high blood cholesterol, high blood pressure, and smoking, are responsible for many cardiovascular diseases. Nevertheless, these risk factors are common in most high- or low-income countries. For instance, about 20% of Canadian adults have elevated blood cholesterol (Public Health Agency of Canada, 2019). Therefore, there has been a call to reduce and manage these modifiable risk factors to control the burden of cardiovascular disease.

Physical inactivity is one of the crucial modifiable risk factors for cardiovascular disease. Mounting evidence suggests the beneficial effects of physical activity in preventing and managing cardiovascular disease (Wahid et al., 2016). Nevertheless, the rate of physical activity is low in many countries. People are also involved in too much sitting, a new cardiovascular risk factor (Katzmarzyk et al., 2020). Socioecological models in health behaviour indicate that several individuals, family, administrative, and policy levels influence people's active and sedentary behaviours (Sallis and Owen, 2015). These models have acknowledged the role of the built environment in promoting an active lifestyle. The built environment is "the human made space in which people live, work, and recreate on a day-to-day basis" (Roof and Oleru, 2008). It includes "homes, schools, workplaces, parks/recreation areas, greenways, business areas and transportation systems" (National Institute of Environmental Health Sciences, 2004). It is hypothesised that built environment attributes can facilitate or impede people's choices to engage in physical activity behaviours in a long-term and sustainable way (Chokshi and Farley, 2014).

Several built environment attributes, such as population density, land-use mix, access to destinations, and availability of green spaces, have been linked to active and sedentary behaviours (Koohsari et al., 2015b; Saelens and Handy, 2008). For instance, a longitudinal study in Australia found that people who moved to well-connected neighbourhoods increased their transportation walking (Knuiman et al., 2014). Another study in the USA found that neighbourhood greenness and walkability were associated with higher physical activity among adult women (James et al., 2017). There is also evidence of the role of the built environment on physical activity and sedentary behaviour in the context of Asia (Motomura et al., 2022; Müller et al., 2020). For example, a study conducted in Japan found that people who lived in neighbourhoods with well-connected streets were more likely to walk and less likely to drive (Koohsari et al., 2017c). Therefore, this evidence suggests that built environment attributes that encourage an active lifestyle in multiple ways can influence cardiovascular health. Nevertheless, the science of modifying the built environment to enhance cardiovascular health outcomes is still in its infancy, with several challenges (Diez Roux et al., 2016; Koohsari et al., 2020a; Koohsari et al., 2021b). Notably, Koohsari et al. (2020a) have identified and categorised these challenges into three categories of conceptual (interactions between activity time and place; behavioural mechanisms; different effects of built environment attributes), methodological (variability in urban design variables; co-existence of urban design characteristics; causality), and policy-relevant issues (built environment standards; separating built environment indices).

1.3. Research aims

The main aim of this research thesis is to address several methodological and policy-relevant issues in the research on activity-friendly built environment characteristics and cardiovascular disease. Notably, this thesis discusses how two built environment tools, Walk Score® and space syntax, can address several of this topic's methodological and policy-relevant issues and explain the next steps and future directions to enhance these tools and concepts.

1.4. Significance of the research

The rise of non-communicable diseases such as cardiovascular disease, cancer, and mental illness is a significant public health problem worldwide. According to the World Health Organization, non-communicable diseases are the leading cause of death in the world, killing about 41 million people each year (World Health Organization, 2021). According to the Ministry of Health, Labor, and Welfare report in Japan, cancer is a leading cause of death, followed by heart disease. Dementia, an umbrella term for mental illness, is also a burden for societies, with over 10 million new cases every year. Therefore, reducing and controlling the major non-communicable diseases has become the focus for global public health organisations and health authorities.

Despite a slight decrease in incidence during the past decade, cardiovascular disease is still ranked among the top four leading causes of mortality (World Health Organization, 2021). Interventions to prevent non-communicable diseases typically focus on individual-level factors (e.g., targeting individuals through behaviour change strategies). However, the increasing prevalence of cardiovascular disease in the world has resulted in growing scientific and political acknowledgement of the necessity for population-based approaches for their possible prevention and management. For example, in Japan, the 'Healthy Japan 21', the official goal developed by the Japanese Ministry of Health, Labor and Welfare to enhance the nation's health, highlights the importance of the built environment on people's health (Ministry of Health, 2012). In Australia, newly-enacted public health legislation explicitly incorporates environmental design (e.g., urban form, transportation, access to green spaces) to promote and support population health. Nevertheless, investigating the role of built environment design on cardiovascular disease is a new research area with several limitations, as identified in my studies (Koohsari et al., 2020a; Koohsari et al., 2021b) in the next chapter.

1.5. Overview of the chapters

This PhD thesis is presented through six chapters which were published as eleven peer-reviewed articles in scientific journals (Koohsari et al., 2020a; Koohsari et al., 2021a; Koohsari et al., 2021b; Koohsari and Oka, 2023; Koohsari et al., 2020b; Koohsari et al., 2023; Koohsari et al., 2019b; Koohsari et al., 2020c; Koohsari et al., 2018b; Koohsari et al., 2018c; Koohsari et al., 2017c).

Chapter one introduces the research problem, aims, and significance of this research.

Chapter two provides a critical literature review of the previous studies on the activity-friendly built environment and cardiovascular disease. This chapter identifies the critical research gaps and next steps in research on this topic (Koohsari et al., 2020a; Koohsari et al., 2021b).

Chapter three describes the validity of using Walk Score® as a practical, easy-to-use tool for measuring walkability in the context of Japan. The first study examined the concurrent validity of the Walk Score® compared with objectively measured walkable built environment variables (Koohsari et al., 2018b). The second study in this chapter explored whether there are also associations between Walk Score® and people's perceived walkable built environment attributes or not (Koohsari et al., 2021a).

Chapter four describes the concept and theory of space syntax and explains how space syntax could be relevant to research on (re)designing activity-friendly built environment (Koohsari et al., 2019b). Notably, it discussed the space syntax theory of natural movement in detail and identified the pathways through which this theory can be linked to active and sedentary behaviours.

Chapter five provides empirical evidence on the role of Walk Score® and space syntax in promoting cardiovascular health. This chapter comprises four studies (Koohsari et al., 2020b; Koohsari et al., 2018c; Koohsari et al., 2017c). The first study explored the associations between Walk Score® and active and sedentary behaviours in Japan (Koohsari et al., 2018c). The second study applied space syntax theory to examine how street layouts were associated with active and sedentary behaviours (Koohsari et al., 2017c). The third study examined the association between space syntax walkability, a newly-developed index, with sedentary behaviours, as the first study of our knowledge (Koohsari et al., 2020b). The fourth study explored how activity-friendly built environment attributes are associated with objectively-assessed cardiovascular risk factors (Koohsari et al., 2023).

Chapter six summarizes the main findings of this PhD research and discusses the main findings. It also provides the next issues that need to be considered to advance research in this field (Koohsari & Oka, 2023).

Figure 1. This PhD thesis structure

Chapter 2. Literature review: built environment and cardiovascular disease

This chapter describes several studies in the literature investigating associations between neighbourhood built environment and cardiovascular risk factors, especially physical inactivity. This chapter critically discussed the literature on this topic in the form of two peer-reviewed papers published in two journals, *Nature Reviews Cardiology* (DOI: 10.1038/s41569-020-0343-6) and *Environmental Research Letters* (DOI: 10.1088/1748-9326/abeadf). These papers identify the key research gaps in the literature on activity-friendly neighbourhood built environment and cardiovascular disease.

2.1. Current knowledge of the built environment and cardiovascular disease

Neighbourhoods — spatial units consisting of land use and roads — include built attributes that influence individuals' health. Although modifying the neighbourhood built environment tends to be difficult in the short term, built environment strategies have long-term effects on behaviour and health (Chokshi and Farley, 2014). Scientific and public interest in the role of the neighbourhood built environment in preventing cardiovascular disease is growing (Nieuwenhuijsen, 2018). Several systematic and narrative reviews have provided preliminary evidence on the associations between a variety of neighbourhood-built attributes, behavioural pathways, cardiovascular disease risk factors and mortality (Chandrabose et al., 2019; Gascon et al., 2016; Kärmeniemi et al., 2018; Nieuwenhuijsen, 2018) (FIG. 1). A systematic review of longitudinal studies and natural experiments found that better availability of destinations and the land-use mix was associated with increased physical activity (Kärmeniemi et al., 2018). A meta-analysis of longitudinal studies found strong negative relationships between neighbourhood walkability and cardiovascular disease risk factors, such as obesity, hypertension and type 2 diabetes mellitus (Chandrabose et al., 2019). A meta-analysis found that more residential green space was associated with reduced cardiovascular disease-specific mortality (Gascon et al., 2016). The links between air/noise pollution, stress and cardiovascular disease have also been recognized (Cohen et al., 2015; Rajagopalan et al., 2018). Although this new, interdisciplinary field of research is promising, knowledge of the relationship between the neighbourhood built environment and cardiovascular disease must be improved. Figure 1 shows the Simplified relationships between the neighbourhood built environment and cardiovascular disease. Preliminary evidence exists on the associations between various neighbourhood built attributes and behavioural pathways and between behavioural pathways and cardiovascular disease clinical risk factors. Research also suggests links between neighbourhood built attributes and pollution, heat and stress, and between pollution, heat and stress, and behavioural pathways and cardiovascular disease clinical risk factors. Accumulating evidence also suggests a socioeconomic status disparity in cardiovascular disease: individuals with lower socioeconomic status tend to have worse cardiovascular disease risk profiles and outcomes (Schultz et al., 2018). In the short and intermediate timeframes, interventions that modify the built environmental conditions under which low socioeconomic status individuals live may be more amendable to change. Such built environmental interventions could have an immediate effect on cardiovascular disease prevention, particularly by encouraging physical activity behaviours.

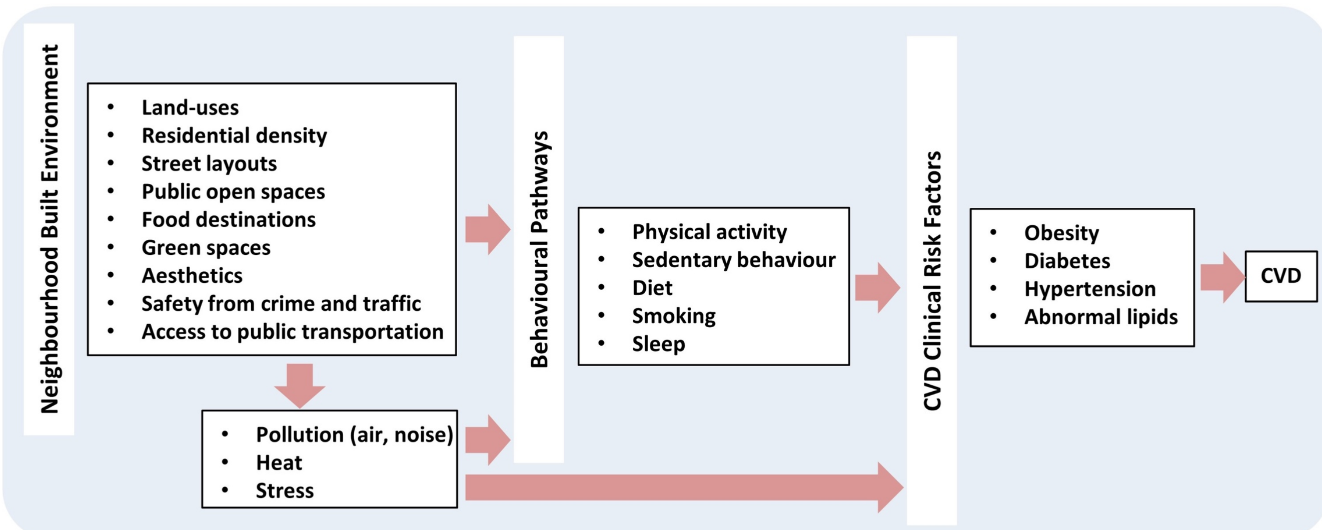


Figure 2. Simplified relationships between the neighbourhood built environment and cardiovascular diseases

2.2. Research gaps on this topic

2.2.1. Conceptual issues

Time and place interactions

Identifying the neighbourhoods to which individuals are exposed is a critical first step in examining built environment– cardiovascular disease relationships. Spatial buffers centred on individuals' residential addresses or administrative boundaries have been used to conceptualize environmental exposures relevant to cardiovascular disease. However, these approaches cannot identify the spatial areas within which people interact daily. People's daily mobility (activity spaces) must be considered when examining built environment–cardiovascular disease relationships because people are exposed to different built attributes in different places during the day (for example, homes, workplaces and parks) (Kwan, 2018). Additionally, exposure to the neighbourhood built environment in terms of time (tenure) and intensity (frequency) is essential for assuming causal links. The use of global positioning system points and ecological momentary assessment (the repeated collection of participants' behaviour and health data in real-time) (Chaix, 2019) within a lifespan approach might help to address the time and place interactions in built environment–cardiovascular disease research.

Mechanisms

The mechanisms by which the neighbourhood built environment might influence cardiovascular disease are not well established. Researchers have examined associations between built attributes and cardiovascular disease behavioural pathways (such as physical activity and diet), and many studies have linked these behaviours with cardiovascular disease risk factors. However, little evidence exists on the mediating roles of these behavioural factors in the observed associations between the neighbourhood built environment and cardiovascular disease. Techniques such as path analysis, mediation analysis and structural equation models can be used to understand better how behaviours mediate links between the built environment and cardiovascular disease. These studies could provide additional evidence for a potential causal link between the built environment and cardiovascular disease.

Differential effects

The same neighbourhood built attribute might have different effects on different cardiovascular disease risk factors and for different population subgroups. For example, whereas high population density might be helpful for adults' weight status (through better availability of physical activity destinations and healthy food options), high population density might also have adverse effects on older adults' blood pressure (through more exposure to air pollution). Examining multiple environmental attributes with multiple behaviours and cardiovascular disease risk factors in single studies can provide insights into the differential effects of the built environment on cardiovascular disease.

2.2.2. Methodological issues

Variability in built environment exposures

Most previous studies have been conducted in heterogeneous areas of low-density, Western countries (Chandrabose et al., 2019). Of note, the effects of the neighbourhood built environment on cardiovascular disease in high-density, compact areas remain unknown. Studies on high-density areas could produce essential insights into how extreme levels of built attributes are related to cardiovascular disease. Even within a single study, maximizing variability in built environment exposure is important to detect dose–response relationships and improve the external validity of the range of built attributes represented in the sample.

Co-existence of built environment attributes

Built attributes co-exist and act together in the actual environment. For instance, although well-connected, dense neighbourhoods with various destinations encourage walking, air pollution might be higher in these neighbourhoods, or food destinations might sell both healthy and unhealthy food. Accounting for all possible built attributes could provide more accurate estimates of the relative contributions of each environmental attribute to cardiovascular disease risk. One study reported a significant negative association between the availability of healthy food shops and the risk of incident atrial fibrillation when accounting for the availability of unhealthy food shops (Garg et al., 2019). Future studies must acknowledge and account for the complex relationships between different built environment exposures and cardiovascular disease.

Causality

Conducting cross-sectional studies is a necessary exploratory step; however, conducting prospective studies that account for residential self-selection could help to establish causality between the built environment and cardiovascular disease. Of note, the lack of data on historical built environment attributes to be linked to the current cohort studies of cardiovascular disease is one of the major limitations. Additionally, residential address information for participants in cohort studies on cardiovascular disease might not be available across all study waves or might not be updated during a participant's involvement in the study. Therefore, identifying whether residents who moved to a more or less health-supportive built environment have better or worse cardiovascular disease risk profiles compared to non-movers remains challenging. The length of time for a follow-up study must also be considered, given that substantial changes in clinical cardiovascular disease risk factors are unlikely over a short period. Further awareness of the relevance of the built environment for cardiovascular disease can help update current cohort studies on cardiovascular disease with complete spatial information to facilitate longitudinal studies.

2.2.3. Policy-relevant issues

Developing built environment benchmarks

Previous studies have mainly been concerned with 'associations' between neighbourhood built environment and cardiovascular disease. Although investigating these associations is a necessary initial step, these studies cannot provide urban designers and policymakers with 'benchmarks' for translating the findings into practice. For example, when we find a positive association between residential density and cardiovascular disease, the next important question is 'how much' and 'where' residential density is needed to influence cardiovascular disease. These benchmarks might also vary depending on different regions and countries. Future research should identify the optimal levels and spatial locations of neighbourhood built environment attributes beneficial for cardiovascular disease.

Dissecting built environment composite indices

Built environment composite indices, such as walkability (for example, the Walk Score®) and sprawl indices, have been examined in relation to cardiovascular disease. Many built environment attributes co-exist, but overhauling entire communities is not always possible, although individual features might be more amendable to modification (such as installing pedestrian pavements). Examining the effects of individual neighbourhood built environment attributes (along with composite indices) on cardiovascular disease is necessary to provide an evidence base for urban designers and policymakers. The focus on individual built attributes also identifies those attributes that have the greatest effect on cardiovascular disease.

2.3. Chapter summary and conclusions

This chapter presented a comprehensive examination of previous studies examining how neighbourhood built environment may be related to cardiovascular risk factors, with particular emphasis on physical inactivity. This chapter was published as two peer-reviewed papers. These papers highlighted the main research gaps in activity-friendly neighbourhood built environment and cardiovascular disease. This PhD research specifically targeted the following three significant methodological and policy-relevant gaps that were identified in these papers:

- Co-existence of built environment attributes.
- Difficulties in translating the findings.
- Developing built environment benchmarks.

In the forthcoming chapters, two built environment tools, namely Walk Score® and space syntax, will be introduced. These tools have the potential to effectively address these three gaps in the literature.

Chapter 3. Validation of Walk Score®

This chapter comprises two studies in the form of two published peer-reviewed papers. The first study aimed to examine the validity of Walk Score® in relation to objectively-measured built environment attributes (Koohsari et al., 2018b). The second study examined how Walk Score® can be related to perceived measures of the built environment (Koohsari et al., 2021a).

3.1. Walk Score® and objective built environment measures

3.1.1. Introduction

Ecological models of physical activity have highlighted the importance of the built environment in shaping people's behaviour, such as walking (Sallis and Owen, 2015). Measuring environmental attributes is essential in understanding the built environment's role in physical activity (Brownson et al., 2009). Objective measures of environmental features computed using geographic information systems (GIS) are frequently used for this purpose (Sallis, 2009). However, this method requires detailed geographic data, which are often not readily available. For example, the Walkability Index (Frank et al., 2010), which has been shown to be associated with walking (Carlson et al., 2015; Owen et al., 2007a), typically consists of four components: intersection density, net residential density, land use mix, and net retail area ratio. However, except for intersection density, they require cadastre-level data, including property boundary and land use of each land parcel for all private and public land (Frank et al., 2010). These geographical data are difficult to source in low-income countries and high-income ones (Kerr et al., 2013; Salvo et al., 2014). This major limitation deters the application of such objective indices in urban design and public health practice. In addition, data management and analysis using GIS software requires trained personnel and special computational equipment, which is an additional limitation (Brownson et al., 2009). These issues highlight the need for easily-available tools that characterize environmental attributes relevant to physical activity.

Walk Score® is a free, publicly available web-based tool that calculates a score in relation to access to local destinations for a given location. Using a decay function, Walk Score® first assigns a raw score to each location based on their network distance to destinations such as grocery shops, restaurants, bookstores, banks, schools, fitness centres, and parks within 1.6 km from that location (Front Seat Management, 2017). These raw scores are then normalized from 0 to 100 with the adjustment of two street network measures (intersection density and block length) around each location (Nykiforuk et al., 2016). Higher scores represent areas with more local destinations nearby, where walking is an easy option for shopping and errands. Source maps obtained from Google, Education.com, Open Street Map, and other open-source data are used to calculate Walk Score® (Front Seat Management, 2017; Nykiforuk et al., 2016). Several studies have found positive associations of Walk Score® with walking for transport (Cole et al., 2015) and with recreational physical activity in small towns (Thielman et al., 2015) and negative associations of Walk Score® with body mass index (Hirsch et al., 2014). For example, a study in Australia found that participants who lived in areas of the top Walk Score® category (highly walkable) were twice more likely to walk 30 minutes or more for transportation per day compared with those who lived in areas of the bottom category (very car dependent) (Cole et al., 2015). Another study in the USA found moving to a location with a higher Walk Score® to be associated with a reduction in body mass index (Hirsch et al., 2014). Nevertheless, several studies report null (Chiu et al., 2015) or negative (Hajna et al., 2015; Tuckel and Milczarski, 2015) associations between Walk Score® with leisure physical activity, recreational walking, and daily steps.

Walk Score® is a commercial product, and its detailed algorithm for calculating a score is not open to the public. In addition, it is unknown whether different countries use comparable methods in constructing the base map (i.e., the way destinations are sourced, categorized and geocoded) from which Walk Score® is derived. Thus, in order to make sure that Walk Score® provides a reasonable measure of walkability outside the countries where Walk Score® has been validated (USA, Australia, Canada), its concurrent validity, i.e., correlation with other environmental attributes known to be associated with walking, needs to be examined.

To date, few studies have examined the concurrent validity of Walk Score® (Carr et al., 2010, 2011; Duncan et al., 2013; Duncan et al., 2011; Nykiforuk et al., 2016). For example, a Canadian study found a high to a very high correlation between Walk Score® and an index of walkability consisting of street connectivity and access to destinations (Nykiforuk et al., 2016). Another study in four metropolitan areas in the USA found positive correlations between Walk Score® and walkability measures such as street connectivity and density of retail destinations (Duncan et al., 2011). However, it is unknown how Walk Score® is correlated with other environmental attributes related to walking in regions or countries outside North America. Concurrent validity needs to be checked locally because the source and process of constructing the base map are unknown.

To check whether Walk Score® can be used as a measure of walkability in Japan, the current study examined the correlation between Walk Score® and attributes of neighbourhood environments relevant to walking for residential addresses chosen from an urban and a rural area in Japan.

3.1.2. Methods

Address data

Residential address data were collected as a part of the Healthy Built Environment in Japan (HEBEJ) project. The HEBEJ project, conducted at the Faculty of Sport Sciences, Waseda

University, aims to identify the environmental determinants of health behaviours and outcomes in Japan. Residential addresses of two localities, Nerima Ward (urban area) and Kanuma City (rural area) were identified in 2011 (to recruit study participants). Guided by the method of the International Physical Activity and the Environment Network (IPEN) studies (Kerr et al., 2013), the study selected participants from high-walkable (Nerima Ward) and low-walkable (Kanuma City) areas. Larger variability in environmental attributes helps to accurately assess correlations as the study areas cover almost the full range of Walk Score®. Nerima Ward is part of the Tokyo Metropolitan area with 716,000 residents and an area of 48 km2, and Kanuma is located about 120 km north of Tokyo with 102,000 residents and an area of 491 km2. A total of 1,500 residents aged 40 to 69 years were randomly selected from the registry of residential addresses (balanced in gender and age group) from each city, and a postal questionnaire was sent to them. Of these, 1,076 participants (569 from Nerima and 507 from Kanuma) responded to the questionnaire and agreed to attend the HEBEJ study. The residential addresses of these participants were geocoded and used in this study. This process received prior ethics approval from the Institutional Ethics Committee of Waseda University (2010-238).

Measures

Walk Score®. Each residential address was manually entered into the Walk Score® website (www.walkscore.com) by two independent project members in 2016. The first author checked and rectified the discrepancy between the two members. Walk Scores® were examined as continuous values.

Built environment attributes. Using GIS, five environmental attributes were calculated within an 800 m circular buffer of each residential address. They included (1) population density (the number of residents per km^2); (2) intersection density (the number of three-ways or more intersections per km2); (3) access to destinations: in line with a previous study (Carr et al., 2011), the number of destinations for the following eight types: food outlets, grocery stores, parks, schools, libraries, fitness facilities, drug stores, and retail per km2); (4) sidewalk availability (the length of roads with sidewalks per km2); (5) access to public transportation (the number of train stations and bus stops per km2). The eight chosen destination types were similar to those used in a previous study (Carr et al., 2011). GIS data (population points, street centerlines, destinations, sidewalks, and public transportation stations) were sourced from the Environmental Systems Research Institute (ESRI) Japan data in 2011. These attributes were selected based on previous evidence showing their associations with walking (Saelens and Handy, 2008; Sugiyama et al., 2012b). We included non-destination measures such as residential density and sidewalk availability to assess concurrent validity comprehensively. Since environmental attributes related to walking are often clustered (e.g., higher population density is needed to support retail destinations), it can be argued that Walk Score®, an overall measure of walkability, would perform better if it is associated with multiple environmental attributes related to walking.

Analysis

Descriptive statistics of environmental attributes and Walk Score® were reported. Pearson's correlation coefficient and multivariate linear regression were used to investigate the associations between Walk Score® and attributes of neighbourhood environments using SPSS 20.0. (SPSS, Inc., Chicago, IL).

3.1.3. Results

After excluding addresses where Walk Score® was not available (n=4), data from 1,072 addresses were analyzed. Table 1 shows the environmental characteristics of the study areas. The mean Walk Score® was 62.2 (SD = 27.5), ranging from 0 to 97. Table 1 also shows the correlation coefficients between Walk Score® and the environmental attributes. Significant positive correlations were observed between Walk Score® and all five environmental attributes assessed. Significant positive correlations were also between Walk Score® and each type of destination. The r-squared value from the multivariate linear regression indicates that about 80% of the variation in the Walk Score® can be explained by five environmental attributes.

Table 1 . Characteristics of the study areas and correlation coefficients between Walk Score® and environmental attributes

Environmental attributes	Mean (SD)	r
Population density [a]	9521 (8115)	0.72***
Intersection density [b]	354 (230)	0.81***
Local destinations [c]	61.9 (52.2)	0.77***
Food outlets	5.8 (8.3)	0.54***
Grocery stores	8.4 (7.7)	0.73***
Parks	3.1 (3.7)	0.49***
Schools	5.2 (4.0)	0.71***
Libraries	0.3 (0.5)	0.42***
Fitness facilities	1.5 (2.1)	0.48***
Drug stores	8.9 (8.0)	0.74***
Retail	28.6 (24.7)	0.74***
Sidewalk availability [d]	12170 (7664)	0.76***
Access to public transportation [e]	12.6 (7.1)	0.76***

*** $p < 0.001$

[a] the number of residents per km^2; [b] the number of intersections per square km^2; [c] the number of destinations per km^2; [d] the length of roads with sidewalks in km per km^2; [e] the number of train stations and bus stops per km^2

3.1.4. Discussion

This was the first study to examine the validity of Walk Score® as a measure of neighbourhood walkability in two communities in Japan. Using over 1,000 residential addresses from urban and rural areas in Japan, our study indicated Walk Score® to be significantly correlated with multiple environmental attributes associated with walking. These findings are consistent with previous studies conducted in the USA and Canada, which showed high correlations between Walk Score® and objective environmental attributes (Carr et al., 2011; Duncan et al., 2011; Nykiforuk et al., 2016). For example, a study in the USA found Walk Score® to be highly correlated with the availability of local destinations (Carr et al., 2011): correlation coefficients were above 0.70 both in this American study and in the present study.

Since Walk Score® is a destination-based index, it was expected to correlate significantly with the number of destinations. Walk Score® was also found to be significantly correlated with the other non-destination measures (population density, intersection density, sidewalk availability, and access to public transport). Another study in the USA also found Walk Score® to be positively associated with population density (Carr et al., 2010). It is plausible that areas with more local destinations have higher population density, higher street connectivity, longer sidewalks, and better access to public transport stops. Studies have shown correlations between these environmental factors (Frank et al., 2005). For example, it has been shown that areas with well-connected streets tend to have many local shops

(Koohsari et al., 2017a). This study suggests that Walk Score® captures not only access to local destinations but also the characteristics of routes to them, which are crucial to facilitating walking (Sugiyama et al., 2012b).

This study had some limitations. There was a temporal mismatch between objective environmental measures (based on the 2011 geographic data) and Walk Score® (extracted in 2016). The objective environmental measures were calculated within an 800 m circular buffer area around each address, while Walk Score® was calculated based on destinations within a 1.6 km network distance from each address. The difference in the buffer sizes used and the way buffers were drawn may not be critical as Walk Score® was calculated using a distance decay function: destinations within 800 m are given much higher weights than those beyond 800 m (Nykiforuk et al., 2016). In addition, the fact that the study found significant correlations under these circumstances suggests that Walk Score® is associated at least with environmental attributes measured within an 800 m buffer area, in which most walking trips occur (Daniels and Mulley, 2013; Millward et al., 2013). Regardless of these issues, this study found evidence supporting the validity of Walk Score® in measuring the walkability of local areas in Japan.

3.2. Walk Score® and perceived built environment measures

3.2.1. Introduction

Evidence suggests that the built environment influences levels of physical activity, which is important for public health. Physical inactivity is known as one of the leading risk factors for global mortality, causing approximately 9% of deaths globally (Lee et al., 2012). It has been established as an important modifiable risk factor for a range of chronic diseases, such as cardiovascular disease, type 2 diabetes, and cancer (Al Tunaiji et al., 2014; Diez Roux et al., 2016; Wahid et al., 2016). Nevertheless, the prevalence of physical inactivity is high worldwide: data from 168 countries showed that approximately 27.5% of the world's adult population was physically inactive in 2016 (Guthold et al., 2018). Physical inactivity also represents a high economic cost for health organisations, costing healthcare systems at least 53.8 billion international dollars worldwide in 2013 (Ding et al., 2016; Pratt et al., 2014). Therefore, developing strategies to improve physical activity closely matches several sustainable development goals (SDGs) (Nugent et al., 2018; United Nations, 2015).

Socioecological models in health behaviours have highlighted the built environment's role in promoting physical activity (Sallis and Owen, 2015). The built environment refers to 'the part of the physical environment that is constructed by human activity, such as houses, shops, workplaces, and public open spaces (Saelens and Handy, 2008). Mounting evidence suggests links between several built environment attributes and people's physical activity (Durand et al., 2011; Kärmeniemi et al., 2018; McCormack and Shiell, 2011). For example, a systematic review of 33 studies found that higher population density, well-connected streets, and various nearby destinations supported physical activity (McCormack and Shiell, 2011). Another systematic review found that better access to destinations and infrastructure for active travel was associated with higher total and transport-related physical activity (Kärmeniemi et al., 2018).

Measuring built environment attributes is a crucial step in conceptualising the built environment in relation to physical activity (Brownson et al., 2009). Two measures, perceived and objective, have been commonly used in studies examining the built environment and physical activity (Lin and Moudon, 2010). Perceived measures of the built environment are obtained by asking residents about their surrounding built environment attributes conducive to physical activity. Several questionnaires, such as the Neighbourhood Environment Walkability Scale (Saelens et al., 2003a), the St. Louis instrument (Brownson et al., 2001), the Environmental Supports for Physical Activity Questionnaire (SIP 4-99 Research Group, 2007), and the Physical Activity Neighbourhood Environment Scale (Sallis et al., 2010) have been used to capture residents' perceptions of the built environment. Objective measures of built environment attributes are collected by audit tools or GIS. Nevertheless, both perceived and objective measures of the built environment have limitations. While perceived measures of the built environment are relatively easy to collect, these measures are subject to reporting bias (Brownson et al., 2009; Weiss et al., 2010), which may require translation and validation within specific populations, and a low response rate is a challenge for both interview and self-administered questionnaires (Brownson et al., 2009; Lee et al., 2011). Objective measures of the built environment require detailed spatial data, which are often not readily available or are costly to collect (Adams et al., 2014a; Salvo et al., 2014; Wilson et al., 2012). For example, GIS measures of the built environment, such as land use mix, net residential density, and retail area, are highly dependent on access to fine-grained geographical data, which makes sourcing them difficult even in high-income countries (Kerr et al., 2013). These issues underscore the necessity of comparing objective and perceived measures of the built environment, characterising the activity-friendly built environment in different contexts.

A growing body of research has investigated the association between Walk Score® and physical activity (Chudyk et al., 2017; Cole et al., 2015; Koohsari et al., 2019a; Koohsari et al., 2018c; Towne et al., 2016; Twardzik et al., 2019). For instance, a Canadian study found that Walk Score® was associated with a greater probability of older adults walking for transport (Chudyk et al., 2017). Another study conducted in Japan found that a higher Walk Score® was associated with walking for commuting and walking for errands (Koohsari et al., 2018c). Walk Score® has also been examined in relation to other health biomarkers that are associated with physical activity, such as body mass index, blood lipid levels, and blood pressure (Braun et al., 2016a; Chiu et al., 2016; McCormack et al., 2018; Méline et al., 2017).

Despite being publicly available, Walk Score® is a commercial product, and its detailed algorithm is not accessible to the public. Additionally, Walk Score® uses data sources obtained from Google, Factual, Great Schools, Open Street Map, and other open-source data (Walk Score, 2020). Different rules and methods were likely used to construct these base maps in each area. For instance, different raster-based and vector-based methods can be used in generating street maps. Defining and geocoding commercial destination points are also not the same across the areas. This causes a comparability issue for the Walk Score® output derived from these maps, especially for regions outside of North America (Koohsari et al., 2018b). Thus, it is necessary to examine whether Walk Score® is correlated with other built environment attributes supportive of walking in different contexts.

Several studies have examined the concurrent validity of Walk Score® for estimating objective built environment measures in the U.S. (Carr et al., 2010; Duncan et al., 2013; Duncan et al., 2011), Canada (Nykiforuk et al., 2016), and more recently in Japan (Koohsari et al., 2018b). For instance, a study conducted in the U.S. found that Walk Score® was positively associated with several objective neighbourhood walkability measures calculated within an 800-metre buffer around residential addresses (Duncan et al., 2013). Another study conducted in Japan found significant positive correlations between Walk Score® and objective built environment attributes relevant to walking (Koohsari et al., 2018b). A limited number of studies have also found significant correlations between Walk Score® and perceived built environment attributes (Bereitschaft, 2018; Carr et al., 2010; Consoli et al., 2020; Frehlich et al., 2020; Lo et al., 2019; Silveira and Motl, 2020; Tuckel and Milczarski, 2015). All these studies were conducted in the U.S. and Canada; to the best of our knowledge, no study has examined the correlations between Walk Score® and perceived built environment attributes in regions or countries outside of North America. Walk Score® does have similarities across regions, but perceptions of built environment attributes are likely to differ to a greater extent across populations. The perceived built environment is a slightly different construct from the objective built environment. While perceptions of one's surrounding neighbourhood are determined mainly by the objective built environment, they are also influenced by people's awareness of their environment, attitudes, beliefs, etc. This means that perceptions of the built environment can be modified by more than making physical changes to the environment by improving awareness of existing facilities and changing attitudes. Examining correlations between perceived and objective measures of the built environment is important from this perspective, as this can inform the types of changes that should be made to perceptions that may ultimately result in more physical activity within the built environment and better health.

Therefore, this study examined the relationships between Walk Score® and perceived walkable environmental attributes in ultrahigh density areas in Japan.

3.2.2. Methods

Data source and participants

Cross-sectional data were collected from an epidemiological study to identify social and urban design correlations between sedentary behaviour and physical activity among middle-aged adults in Japan. The study design and recruitment procedure details have been described elsewhere (Ishii et al., 2018; Koohsari et al., 2020d). Briefly, data were obtained between July and December 2013 and April 2014 to February 2015 from a randomly selected sample of residents living in two Japanese urban localities, Koto Ward and Matsuyama City. An invitation letter was sent to 6,000 adult residents (aged 40–64 years), randomly selected from the government registry of residential addresses (balanced by gender and age group). A total of 866 individuals agreed to participate in the study (response letter = 14.4%), of which 779 completed a self-administrative questionnaire. These participants were offered a book voucher (¥1000, equivalent to approximately USD 10). The Institutional Ethics Committee of Waseda University approved this study (2010-238).

Measures

Walk Score®. Walk Score® is a free, openly available web-based tool that provides an objective walkability score for any given location. Walk Score® uses a decay function to assign a raw score to each location based on its network distance to nearby amenities such as stores, cafes, bookshops, parks, and restaurants within a mile from that location (Walk

Score, 2020). Population density and road metrics such as block length and intersection density were taken into account to calculate the final scores ranging from 0 to 100. Higher scores indicate areas that are conducive and supportive of walking. Each participant's residential address was entered into the Walk Score® publicly available interface (www.walkscore.com) by two independent project members in 2016. Disagreements between the two researchers were checked and rectified by the first author. Continuous Walk Score® values were examined in this study.

Perceived walkable environment attributes. The perceived walkable built attributes were evaluated using the Japanese version of the International Physical Activity Questionnaire Environmental Module (IPAQ-E) with a 4-point Likert scale (strongly agree, somewhat agree, somewhat disagree and strongly disagree). The IPAQ-E has demonstrated good test-retest reliability in Japanese adults (Inoue et al., 2009). Nine items of the IPAQ-E were included (Inoue et al., 2009): (1) population density ('What is the main type of housing in your neighbourhood?' For this question, the five answers were detached single-family housing; apartments with 2–3 storeys; a mix of single-family housing and apartments with 2–3 storeys; condos with 4–12 storeys; and condos with >13 storeys); (2) access to shops ('Many shops, stores, markets or other places to buy things I need are within easy walking distance of my home'); (3) access to public transport ('It is within a 10–15 minute walk to a transit stop from my home); (4) presence of sidewalks ('There are sidewalks on most of the streets in my neighbourhood'); (5) presence of bike lanes ('There are facilities to bicycle in or near my neighbourhood, such as special lanes, separate paths or trails, shared use paths for cycles and pedestrians'); (6) access to recreational facilities ('My neighbourhood has several free or low-cost recreation facilities, such as parks, walking trails, bike paths, recreation centres, playgrounds, public swimming pools, etc.'); (7) aesthetics ('There are many interesting things to look at while walking in my neighbourhood'; (8) traffic safety ('There is so much traffic on the streets that it makes it difficult or unpleasant to walk in my neighbourhood'; (9) safety from crime ('The crime rate in my neighbourhood makes it unsafe to go on walks at night'). Two negative items, including traffic safety and safety from crime, were reverse coded, with higher scores representing a safer environment. In line with several previous studies (Arvidsson et al., 2012; Orstad et al., 2018), perceived overall walkability was measured by summing the nine perceived built environment attributes, resulting in a possible range from 11 to 37 (Cronbach's alpha = 0.70).

Covariates. Participants reported several sociodemographic factors, including 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 ≥ ¥5,000,000).

Statistical Analysis

Descriptive statistics of participants' sociodemographic and perceived walkable environmental attributes were reported. Partial correlation coefficients were used to estimate the correlations between Walk Score® and perceived walkable environmental attributes, including overall walkability, adjusted for covariates. The magnitude of the observed significant correlation coefficients was interpreted using Cohen's guidelines for small ($r > 0.10$), medium ($r > 0.30$), and large ($r > 0.50$) (Cohen, 2013). Analyses were conducted using Stata 15.0 (Stata Corp, College Station, Texas), and the significance level was set at $p < 0.05$.

3.2.3. Results

After excluding missing data on Walk Score® and perceived walkable environmental attributes, data from 756 participants (97%) were analysed. Participants' sociodemographic characteristics are presented in Table 2. The mean age of the participants was 52.2 ± 7.0 years, and approximately 60% were female. The majority of participants were employed (82%), had a high tertiary educational attainment (64%), were couples (79%), lived with others (89%), and had an annual gross household income lower than ¥5,000,000 per year (53%).

Table 2. Characteristics of study participants (N=756)

Variable	**Mean (SD) or N (%)**
Age (years)	52.2 (7.0)
Gender	
Female	455 (60.2)
Male	301 (39.8)
Working status	
Employed	620 (82.0)
Unemployed	131 (17.3)
Missing	5 (0.7)
Highest education	
Tertiary	483 (63.9)
Below tertiary	269 (35.6)
Missing	4 (0.5)
Marital status	
Single	155 (20.5)
Couple	596 (78.8)
Missing	5 (0.7)

Living status	
Alone	85 (11.2)
With others	671 (88.8)
Gross annual household income	
<¥5,000,000	402 (53.2)
≥ ¥5,000,000	337 (44.6)
Missing	17 (2.2)

Mean scores for perceived walkable environmental attributes are shown in Table 3. The mean Walk Score® was 73.0 (SD=25.0), ranging from 0 to 100. Adjusted for covariates, positive correlations were observed between Walk Score® and several perceived walkable environmental attributes. There was a large correlation between Walk Score® and access to shops (0.58; $p < 0.001$). There were medium correlations between Walk Score® and population density (0.38; $p < 0.001$), access to public transport (0.34; $p < 0.001$), presence of sidewalks (0.41; $p < 0.001$), and access to recreational facilities (0.37; $p < 0.001$), and there was a small correlation between Walk Score® and the presence of bike lanes (0.16; $p < 0.001$). There was a small negative correlation between Walk Score® and traffic safety (-0.13; $p < 0.001$). No significant correlations were found between Walk Score® and aesthetics or between Walk Score® and safety from crime. There was a medium correlation between Walk Score® and overall perceived walkability (0.48; $p < 0.001$).

Table 3. Partial correlation coefficients between Walk Score® and perceived walkable environmental attributes (N=756)

Variable	M±SD	Unadjusted r	P	Adjusted r [a]	P
Population density	2.60 ± 1.65	0.44	< 0.001	0.38	< 0.001
Access to shops	3.02 ± 1.02	0.58	< 0.001	0.58	< 0.001
Access to public transport	3.62 ± 0.78	0.37	< 0.001	0.34	< 0.001
Presence of sidewalks	3.17 ± 0.97	0.44	< 0.001	0.41	< 0.001
Presence of bike lanes	2.04 ± 1.08	0.18	< 0.001	0.16	< 0.001
Access to recreational facilities	2.84 ± 1.04	0.39	< 0.001	0.37	< 0.001
Aesthetics	2.70 ± 0.85	-0.02	0.61	-0.06	0.08

Traffic safety	3.11 ± 0.81	-0.10	< 0.05	-0.13	< 0.001
Safety from crime	3.20 ± 0.76	0.06	0.08	0.06	0.13
Overall perceived walkability	26.30 ± 5.00	0.52	< 0.001	0.48	< 0.001

[a] Adjusted for age, gender, working status, highest education, marital status, living status, and gross annual household income.

The maximum value for perceived population density and for other perceived built environment attributes was 5 and 4, accordingly. The maximum value for overall perceived walkability was 37.

3.2.4. Discussion

In this study, as the first study conducted in Asia, we aimed to examine the correlations between Walk Score® and perceived walkable environment. We found that Walk Score® was significantly positively correlated with several perceived walkable environmental attributes, including population density, access to shops, public transport, recreational facilities, and the presence of sidewalks and bike lanes. Notably, a large and a medium correlation was observed between Walk Score® and perceived access to shops and between Walk Score® and overall perceived walkability, respectively. Commercial destinations tend to exist in areas with high population densities (i.e., cost-benefit). Therefore, a positive correlation between Walk Score® and perceived population density was expected. These findings are consistent with previous studies conducted in the U.S. reporting small to large associations between Walk Score® and perceived built environment (Carr et al., 2010; Lo et al., 2019; Silveira and Motl, 2020). For example, Silveira and Motl (2020) found significant positive correlations between several perceived built environment measures such as street connectivity, land use mix and residential density (measured using the NEWS-A questionnaire), and Walk Score®. Lo et al. (2019) also found that a higher Walk Score® was significantly correlated with perceived proximity to destinations and having street shoulders. Our results add to these findings and extend them into the Japanese context as an example of Asian ultrahigh density areas.

Several previous studies found that Walk Score® was significantly correlated with objective measures of the built environment in relation to walking (Carr et al., 2011; Koohsari et al., 2018b). However, the magnitudes of the correlation coefficients were mostly larger than those of the perceived built environment measures. People's perceptions of built environment attributes do not always match objective environmental measures, and they do have a distinct influence on people's engagement in active behaviours (Gebel et al., 2009; Gebel et al., 2011; Koohsari et al., 2015a). Therefore, it is suggested that strategies to promote physical activity should target both the objective environment and people's perceptions of the environment (Koohsari et al., 2015a). Our findings together with the results from the studies examining Walk Score® and objective built environment measures, suggest that Walk Score® can be useful as an evaluative intervention tool, as it can represent (to some degree) both objective and perceived measures of the built environment related to walking.

We also identified that Walk Score® was related to the presence of bike lanes. It is likely that a walkable area with high density and a variety of destinations nearby attracts cyclists and benefits from bike infrastructure. However, built environment features conducive to walking are not necessarily the same as those beneficial for biking (Forsyth and Krizek, 2011). Further research is needed to explore whether Walk Score® is correlated with other built environment features beneficial for biking. No significant correlations were observed between Walk Score® and aesthetics and safety from crime. This does not necessarily mean that aesthetics and safety from crime have limited importance for walking behaviour. While the influence of these factors on walking has only received limited interest, some have pointed to their significance (Mehta, 2008). Aesthetics and safety from crime are micro-scale urban design qualities that Walk Score® does not attempt to measure. Future studies can match a street segment with excellent micro-scale urban design qualities and another with poor qualities for a survey of residents' perceptions in the surrounding area.

A small negative correlation was observed between Walk Score® and traffic safety. This is consistent with a previous study, which found a small positive correlation between Walk Score® and perceived traffic hazards (Silveira and Motl, 2020). Since the Walk Score® algorithm does not include any traffic-related items (at this stage), it is unknown whether the observed correlation between Walk Score® and traffic safety is spurious or whether there is a plausible link. While highly walkable areas characterised by various destinations and well-connected streets are attractive for pedestrians, such areas may also inevitably draw motor vehicles. A study conducted in the U.S. found that higher street connectivity was associated with more accidents between cars and people and among cars (Marshall and Garrick, 2011). Another study in Canada found that residents in walkable neighbourhoods, those with good street connectivity and destinations, had significantly lower perceived traffic safety (Jack and McCormack, 2014). Thus, traffic safety may be a concern for residents in areas with higher Walk Score® values, where many pedestrians and cars interact.

This study has some limitations. Most of the participants in our sample were involved in a couple's relationship and lived with others, and we had a low response rate. These may limit the generalisability of our findings. There was a temporal mismatch between our perceived built environment measures (based on the survey in 2013-2015) and Walk Score® (extracted in 2016). However, changes in the built environment (macrolevel) are relatively stable in the short term (Clary et al., 2020; Hirsch et al., 2014). Additionally, the Walk Score® company did not release a detailed procedure on how they account for road metrics in their final Walk Score®. This study did not capture other factors, such as physical activity behaviour and exposure to or interaction with their neighbourhood built environment, which may influence perceptions.

3.3. Chapter summary and conclusions

This chapter encompassed two individual studies, presented as published peer-reviewed papers. The primary focus of the first study was to investigate the validity of Walk Score® in relation to GIS-based measures of the built environment. This study found that Walk Score® was positively correlated with several objectively-measured built environment attributes. The second study aimed to test how Walk Score® may be related to perceived measures of the built environment. High positive correlations were also found between Walk Score® and perceived measures of the built environment.

Walk Score® is a readily-available tool that allows urban designers, government officials, and public health practitioners to identify the walkability of local areas without relying on detailed geographic data or GIS expertise. Since Walk Score® is an overall indicator, it does not provide information about what aspects of the environment may need to be modified to promote physical activity. Nonetheless, it assists practitioners in locating areas that hinder residents from being active and would inform future interventions. The first study found that Walk Score® is a valid measure of walkability in Japan. However, a further country-specific validity check is necessary to expand its application to other countries, where obtaining detailed geographic data is challenging. The second study's findings highlight that Walk Score® was correlated with several perceived walkable environment attributes in the context of ultrahigh density areas in Asia. Further research is needed to confirm these findings in other countries and areas.

In the following chapter, space syntax will be introduced, emphasising its contributions to research on active living. It will be discussed how space syntax can contribute to research on active living.

Chapter 4. Space Syntax and active living research

This chapter describes how space syntax theory and concept are relevant to research on active living and discusses the potential for applying this concept in this area of research. This chapter was published as a peer-review paper in *Health & Place* journal (Koohsari et al., 2019b)

4.1. Space syntax and walking behaviour

4.1.1. Built environment and walking for transport

Physical inactivity is one of the main contributors to the global public health burden of non-communicable diseases, particularly type 2 diabetes and cardiovascular disease (World Health Organization, 2017b). Most urban-dwelling adults are, however, insufficiently active for preventive health benefits (Hallal et al., 2012). Walking for transport to get to/from local destinations, including shops, services, and transit stops, is a major source of adults' health-related physical activity (Chaix et al., 2014) and is consistently associated with better health (Kelly et al., 2014; Murtagh et al., 2010). Its health benefits can outweigh the associated risks of trauma through traffic incidents and exposure to air pollution (Mueller et al., 2015). Due to its potential to be integrated into daily life, walking is argued to be a practical and sustainable way to promote regular physical activity for improved health outcomes (Lee and Buchner, 2008). "Active living research," which aims to create activity-friendly communities, has shown that neighborhood built environment attributes are related to residents' walking for transport (Giles-Corti et al., 2016; Sallis et al., 2016; Sallis and Owen, 2015). In order to identify environmental features supportive of walking, the built environment first needs to be operationalized and measured. Over the past decades, this research field has developed several measurement methods to characterize such environmental attributes (Brownson et al., 2009; Eyler et al., 2015). A measure of "walkability" has been used widely: An index consisting of four components (residential density, land use mix, street connectivity, and retail site design) has been shown to be associated with walking for transport (Frank et al., 2010).

4.1.2. Street layout and land use: urban form and function

Street connectivity is a component of walkability related to urban form. It is concerned with street layout, particularly the directness of routes between two locations (e.g., home and shopping venues) in a street network (Handy et al., 2003). It has typically been measured as intersection density (i.e., the number of intersections with three or more intersecting streets divided by area size), using street centerline data, which are commonly available from local governments, public sectors dealing with roads and water distribution, or an open source (e.g., OpenStreetMap, Google). Greater street connectivity has been found to be consistently associated with higher levels of walking (Badland et al., 2008; Koohsari et al., 2014c).

Land use mix, which refers to having a variety of services, retail outlets and other amenities within an area, represents a functional aspect of urban land. It is hypothesized that higher land use mix is conducive to more walking for transport, but literature reviews have shown inconsistent findings on the association of land use mix with walking for transport (Durand et al., 2011; Grasser et al., 2013). This may be partly because the land use mix relates to the presence of different uses (any land uses) rather than to the presence of specific land uses that may provide destinations for walking. There are also issues of data availability and comparability. Calculating land use mix requires parcel-level land use data, often difficult to obtain or unavailable (Lotfi and Koohsari, 2011; Salvo et al., 2014). Another issue is the comparability of base land-use data: different land use categories are often used in different localities. Producing comparable land-use mix measures across areas can be challenging, even when land-use data are available (Mavoa et al., 2018).

4.1.3. Space syntax as a measure of street connectivity

Space syntax offers an alternative way of measuring street connectivity. Originating from architecture and urban design, space syntax is commonly understood to be a method to characterize and quantify the spatial layout of enclosed spaces within buildings or streets within urban space, using topological approaches (Hillier and Hanson, 1984; Hillier et al., 1987). Unlike intersection density, space syntax measures focus on topological distance within a network, i.e., the number of turns needed to reach from one location to another (Bafna, 2003; Peponis et al., 1997). The process for calculating space syntax measures has been explained elsewhere (Bafna, 2003; Hillier and Hanson, 1984; Koohsari et al., 2014a; Peponis and Wineman, 2002) and will not be described in detail here. Briefly, street integration, a key space syntax measure, shows how "accessible" a street segment is topologically from all other street segments within a defined area (e.g., a certain distance from the center of the street). A higher integration value for a street segment means that fewer turns are required to reach the segment from other streets within the network. Figure 2-a shows a street network, and Figure 2-b shows the levels of integration (darker lines are higher in integration). Similar to intersection density, space syntax measures can be calculated based only on street centerline data, using a specifically developed yet open software (Turner, 2004).

Space syntax measures have been used to indicate street connectivity in active living research (Baran et al., 2008; Koohsari et al., 2017b). This entails an additional step, as this area of research is concerned with environmental attributes at the scale of the neighbourhood. Since space syntax measures are calculated for each street segment, they need to be aggregated into an area-level measure (e.g., a "buffer" area within a certain distance from home, an administrative area unit); so that their association with walking can be examined (Figure 2-c). Street integration aggregated at this level has been associated with walking in the U.S. (Baran et al., 2008) and Japan (Koohsari et al., 2017c).

Figure 3. Process of calculating space syntax measures: (a) street centerlines (base map); (b) space syntax measure of integration calculated for each street segment (darker lines are more integrated), (c) area-level measures calculated by aggregating integration values within a buffer area from participant's home.

4.2. Space syntax theory of natural movement

Applying the space syntax theory of natural movement to active living research opens up new research avenues to be investigated. We propose the following four topics to gain new insights and advance methods in active living research.

4.2.1. A theory linking urban form and function with pedestrian movement

Natural movement, a theory within space syntax, refers to the ability of the street layout to predict pedestrian movement (Hillier et al., 1993). The theory posits that more integrated streets, likely more accessible from other streets, will draw more pedestrians. Several previous studies have found a positive correlation between higher street integration and a greater pedestrian volume (Foltête and Piombini, 2007; Hajrasouliha and Yin, 2015; Hillier and Iida, 2005; Lerman et al., 2014; Ozbil et al., 2011). There are also established associations between higher intersection density with more walking for transport (Badland et al., 2008; Christiansen et al., 2016; Koohsari et al., 2014c). An often-used explanation for such associations is that travel distance is shorter between two points in areas with well-connected streets (Frank, 2000). However, according to the natural movement theory, what contributes to more pedestrian movement in areas with better street connectivity is the co-location of commercial and public buildings along more integrated streets (Hillier et al., 1993). Empirical studies have indeed shown the association of street integration with the availability of commercial land uses or commercial destinations (Liu et al., 2015; Omer and Goldblatt, 2016; Porta et al., 2012; Rui and Ban, 2014; Tsou and Cheng, 2013; Wang et al., 2014). It has also been shown that areas with well-connected streets are conducive to transportation walking, partly due to the availability of more commercial destinations (Koohsari et al., 2017b; Koohsari et al., 2016b).

Although space syntax methods focus strictly on how streets are connected topologically, the theory of natural movement can link the formal and functional aspects of urban land through pedestrian movement (Hillier et al., 1993). In this regard, the theory of natural movement bridges street layout and destinations (land use), two important environmental elements supporting transportation walking (Millward et al., 2013; Sugiyama et al., 2012b; Wineman et al., 2014; Witten et al., 2012). Figure 3 depicts how built environment factors (form and function) are integrated by the theory of natural movement and influence transportation walking through pedestrian movement.

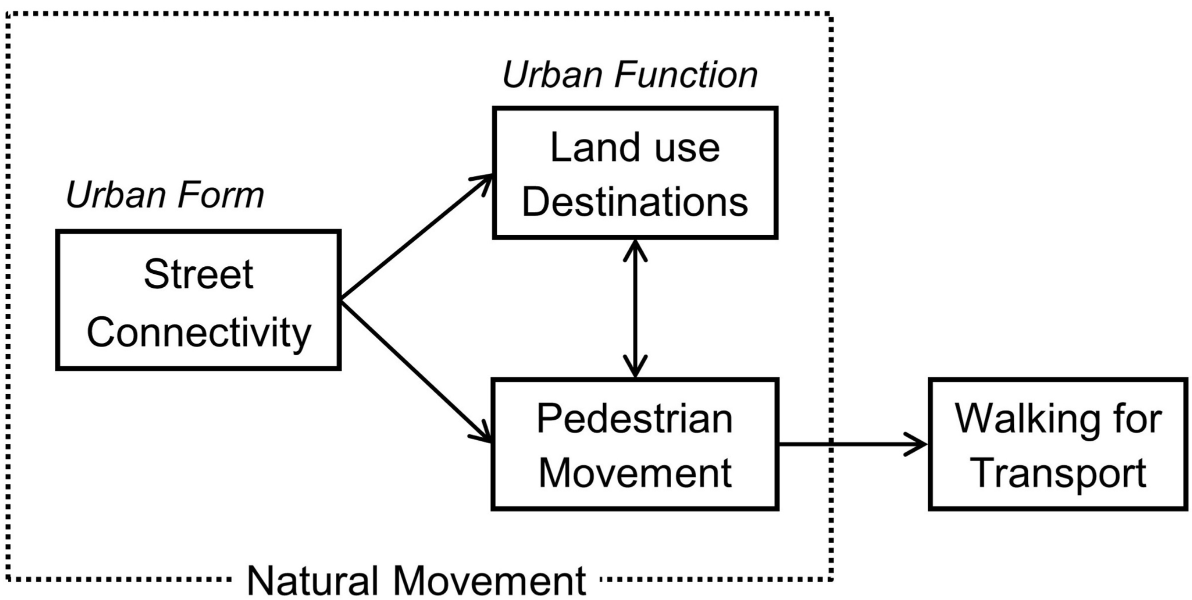


Figure 4. Diagrammatic representation of the theory of natural movement and walking for transport

4.2.2. Space Syntax as a tool for characterizing key attributes of walkability

The theory of natural movement and supporting empirical findings (higher integration means not only higher street connectivity but also the presence of commercial destinations) point to the possibility of using street integration as a new measure of walkability. The walkability index commonly consists of net residential density, street connectivity, mixed land use, and retail site design (Frank et al., 2010). As discussed before, parcel-level land use data are hard to locate, and the data-intensive nature of the walkability index may, in some contexts, limit its broader applications. Developing high-quality yet less data-dependent environmental measures in relation to walking is vital to widen the research base for urban design and public health.

To address the gap, Koohsari et al. (2016a) developed a new walkability index, space syntax walkability (SSW), based on the space syntax theory of natural movement. This index consists of population density and a space syntax measure of integration, which is not only a measure of street layout but can also represent the presence of commercial land use or destinations. As discussed above, street integration is calculated using commonly-available street centerline data with open software. Thus, SSW can be a less data-intensive version of walkability. It has been shown that SSW and the four-component walkability are highly correlated ($\rho = 0.76$) and equally associated with walking for transport in a study conducted in Australia (Koohsari et al., 2016a). Future research needs to examine how

SSW is correlated with walkability and associated with walking for transport in different localities. Once confirmed, SSW can be used as a simplified measure of walkability for areas where detailed land use data are not easily available. It is important to note that walkability is a relative (ranking) measure that is determined within a certain study area. This also applies to street integration, which does not have a unit. In contrast, a more recent measure, Walk Score®, is on an easily interpretable scale (www.walkscore.com). To facilitate the broader utility of SSW not only by researchers but also by practitioners, research needs to develop a benchmark against which the level of walkability can be judged.

4.2.3. Conducting street-level investigations of integration and GPS-based walking

Active living research has been using "neighbourhood" as an area-level unit. Neighbourhoods are defined as an area within a certain distance (buffer) from the participant's residential address or within existing administrative boundaries (e.g., Census Block in the U.S., Output Area in the U.K., Statistical Area in Australia). All environmental factors are calculated within such areas, and analyses examine how these area-level measures are associated with residents' physical activity. However, defining a neighbourhood is not an easy task. It has been shown that buffer areas typically used in research do not match an area considered a "neighbourhood" by residents (Smith et al., 2010) or an activity space captured by global positioning systems (GPS) where their physical activity takes place (Holliday et al., 2017; Kwan et al., 2018). It is also known that the associations between walkability measures and walking differ by the way buffers are drawn (Houston, 2014; Koohsari et al., 2013; Oliver et al., 2007). As discussed above, there are two stages in calculating area-based space syntax measures: the first stage is calculating integration for each street segment, and the second stage is calculating the mean integration for a neighbourhood. Both stages require a defined area in which calculation is to be performed. In principle, the size of these areas should align with the distance that can be walked. However, walkable distances vary by demographic factors, and different sizes specified can produce different space syntax measures. This is the modifiable unit area problem (MAUP), a well-known problem in geography, where any change of boundary in which data are aggregated may produce different results (Openshaw, 1984).

Space syntax measures can transform the way in which relationships between environmental factors and walking are examined, as they allow consideration of the relationships at the scale of streets. Examining how street-level integration is related to pedestrian volume is now possible due to the increasing use of new tracking technologies such as GPS in mobile phones and wearable devices (Althoff et al., 2017; Krenn et al., 2011; Shoval, 2008). Such research may provide a more detailed understanding of street-level attributes that may affect walking for transport.

4.2.4. Conducting natural-experiment studies

The majority of evidence showing relationships between space syntax measures and walking comes from cross-sectional studies. At this point, it is only possible to conclude that environmental attributes identified by space syntax are “correlates” of adults’ walking for transport. There are a few longitudinal studies examining participants’ walking before and after they relocated, which found that moving to areas with better street connectivity was associated with an increase in walking (Knuiman et al., 2014; Wells and Yang, 2008). A cohort study following participants over nine years also found that street connectivity did change during the study period, and improved connectivity was associated with increased walking for transport (Hirsch et al., 2014).

Although the street layout is highly stable in existing neighbourhoods, it occasionally changes. For instance, an infill development may have new streets/paths that connect existing streets. A new park or open space can also link adjacent streets. The addition of such new street segments could change street integration values substantially. Evidence from natural experiments observing such changes to the street network would be highly informative, as this would provide strong indications of causality.

4.2.5. Testing the theory of natural movement

As shown in Figure 3, the space syntax theory of natural movement links street layout and land use with pedestrian movement. In the actual environment, this occurs as an incremental process in which economic activities and pedestrian movement gradually build up along well-connected streets (Omer and Goldblatt, 2016; Scoppa and Peponis, 2015). The co-location process of retail destinations and integrated streets can also be assisted by the agglomeration of commercial destinations and services, enhancing efficiency and convenience of access. It is possible to track such commercial activities over time through various means (e.g., yellow pages and business registration databases). Identifying where commercial destinations increased or decreased according to space syntax measures can be informative to research on active travel and land use planning. Due to land use zoning, commercial land use is not always allocated along well-connected streets. Understanding the characteristics of streets where commercial activities are more likely to grow will help policy-makers and practitioners to make informed decisions about where best to locate commercial and residential land uses.

Research can also examine how the mismatch between land use and street integration (e.g., commercial land use along less-integrated streets) is associated with less walking for transport compared to areas where a match exists. Such research can further testify to the importance of understanding the role of street layout in building neighbourhoods that facilitate walking.

4.3. Chapter summary and conclusions

This chapter presented the basics of space syntax and its conceptual framework in relation to active living research. It discussed the potential implications of incorporating space syntax in this area of research.

To date, active living research has employed space syntax methods as an alternative to intersection density. We argued in this chapter that a concept of space syntax, natural moment, can help advance our understanding of the role of street layout in active living research. The theory of natural movement identifies street layout as a primary factor influencing pedestrian movement within a city (Dhanani et al., 2017; Hillier et al., 1993; Karimi, 2012; Omer and Goldblatt, 2016). Although space syntax methods "were not originally aimed at modelling movement but at understanding the morphological logic of urban space" (Hillier et al., 1993), the theory of natural movement can move active living research forward conceptually, because it provides a link between urban form, function, and walking for transport.

While there have been two previous commentaries in active living research introducing the utility of space syntax in relation to children's physical activity (Cutumisu and Spence, 2009) and adults' park-related physical activity (Koohsari et al., 2014a), they have primarily focused on how to apply space syntax measures. They do not explicitly address the potential for conceptual advancement building on the theory of natural movement. In this chapter, we first explained the theory of natural movement. We illustrated how a well-connected street layout (urban form) enhances walking for transport (pedestrian movement) partly by attracting retail land use (urban function). We then proposed several key research issues that emerged from explicitly incorporating the theory of natural movement in active living research.

Space syntax methods show considerable promise as a parsimonious approach to measuring aspects of urban form in relation to walking for transport. In this article, we have focused on the space syntax theory of natural movement and explored new research avenues that may be opened up by applying this theory. As natural movement enables urban form and function to be linked with pedestrian movement as an underlying element, it can provide insights into the street layout as a multi-dimensional determinant of walking for transport. Although space syntax has been used in urban design/planning, transport, and geography areas for decades, its application to health promotion (through walking) is still limited. Further studies are warranted to make more-explicit use of the theory of natural movement and to apply space syntax methods to inform urban design/planning practices and policies that encourage walking for transport.

In the forthcoming chapter, four studies will be introduced. These studies will provide empirical evidence on how two built environment tools, Walk Score® and space syntax, are associated with active and sedentary behaviours, and cardiovascular biomarkers.

Chapter 5. Empirical evidence and discussions

This chapter comprises four studies in the form of four published peer-reviewed papers. The first study explored the associations between Walk Score® and active and sedentary behaviours in Japan, as the first study on this topic (Koohsari et al., 2018c). The second study examined whether space syntax measures of street layout are associated with active and sedentary behaviours in the context of Japan (Koohsari et al., 2017c). The third study aimed to test the associations between space syntax walkability index and sedentary behaviours, as the first study on this topic (Koohsari et al., 2020b). The fourth study examined the associations between traditional and novel space syntax-based measures of the built environment and cardiometabolic risk factors (Koohsari et al., 2023).

5.1. Walk Score® and active and sedentary behaviours

5.1.1. Introduction

Measuring environmental attributes is important in understanding which areas are more (or less) conducive to residents' active living (Wang et al., 2016). Processing various geographic data using GIS has been a standard way to calculate environmental attributes (Leslie et al., 2007). However, this method requires special expertise in GIS and sufficient resources to gather geographical data, process them (cleaning data, merging with other data), and calculate necessary variables in GIS software (Brownson et al., 2009). Such technical capacity may not be available to many relevant stakeholders, such as local policymakers and developers. Calculating environmental attributes relevant to walking is typically a resource-intensive process (Porter et al., 2004). For example, a conventional walkability index consists of four environmental measures: net residential density, land-use mix, intersection density, and net retail area ratio (Frank et al., 2010). They require land-use data for individual land parcels and retail floor area data for commercial parcels, which can be unavailable or expensive to purchase (Lotfi and Koohsari, 2011; Salvo et al., 2014).

Walk Score® is a website-based, publicly-available tool that assigns a score to a given address based on the proximity of local destinations and street connectivity around that location. Walk Score® was associated with objectively-measured neighbourhood attributes relevant to walking (Carr et al., 2011; Duncan et al., 2011). A higher Walk Score® has also been found to be positively associated with transportation (Brown et al., 2013; Chiu et al., 2015; Cole et al., 2015; Hirsch et al., 2014; Hirsch et al., 2013) and leisure (Hirsch et al., 2013) walking.

However, Walk Score® research has been limited in two important ways. First, the relationship between Walk Score® and walking has been examined only in Western countries such as the United States (Hirsch et al., 2013), Canada (Chiu et al., 2015), Australia (Cole et al., 2015), and France (Duncan et al., 2016). To extend its applicability, it is essential to understand whether Walk Score® is related to active behaviours in non-

Western countries (Duncan et al., 2013). Walk Score® can contribute to a greater understanding of the relationship between built environment attributes and active travel behaviours in Asian countries, where chronic diseases linked to physical inactivity and sedentary behaviours have increased (Ramachandran and Snehalatha, 2010; Yoon et al., 2006). Second, the prolonged sitting time has adverse health effects (Ekelund et al., 2016; Owen et al., 2010), but previous studies have not examined associations of Walk Score® with sedentary behaviours.

Therefore, the current study examined associations of Walk Score® with walking for commuting, errands and exercise and with two sedentary behaviours (TV viewing and car driving) among adults in Japan in a non-Western context.

5.1.2. Methods

Study Settings and Participants

This study used cross-sectional survey data from the Healthy Built Environment in Japan (HEBEJ) project. The HEBEJ project aimed to examine how built environment attributes are related to health behaviours and outcomes among middle-to-older-aged adults. This age group was selected for this project because adults begin to experience age-related functional declines in middle age, which continues through the later stages of life (World Health Organization, 2002). For instance, a 6-year follow-up study on mobility limitations among middle-aged workers (40 to 50 years old) has shown that more than 10% of the participants developed mobility limitations during the study period (Mänty et al., 2014). Another longitudinal study also found that functional decline occurs before and after retirement (van Zon et al., 2016). Given that habitual physical activity is known to be protective against declines in physical function (Morie et al., 2010), it is important to address these daily behaviour patterns of middle-to-older-aged adults. Data from adults living in two areas (Nerima Ward and Kanuma City) were collected in 2011. Nerima Ward is part of the Tokyo Metropolitan area, and Kanuma City is a rural area located about 120 km from Tokyo. A total of 1,500 residents aged 40 to 69 years were randomly selected from the residential addresses (balanced in gender and age group) from each city. Written informed consent was obtained from all respondents. This survey and its linkage with built environment measures received prior approval from the Institutional Ethics Committee of Waseda University (2010-238).

Measures

Walk Score®. The Walk Score® procedure first assigns a raw score to each location based on the availability of destinations such as grocery stores, banks, restaurants, schools, fitness centres, and parks. It uses a decay function according to the network distance to each of them (Front Seat Management, 2017). It then normalizes the score from 0 to 100 by adjusting two street layout measures (intersection density and block length) around that location (Nykiforuk et al., 2016). Higher scores for a location mean more opportunities to walk around that location. The Walk Score® uses source maps from Google, Education.com, Open Street Map, and other open-source data. The detailed procedures for Walk Score® calculation can be found elsewhere (Front Seat Management, 2017; Nykiforuk et al., 2016). To obtain the Walk Score® in this study, each participant's address was manually entered into the Walk Score website (www.walkscore.com) by two independent members in 2016. Walk Scores® obtained were used as a continuous variable.

Dependant variables

Walking behaviours. Using validated questions (Inoue et al., 2010), participants were asked about their walking in the past week for three specific purposes: commuting, errands, and exercise. Two dichotomized walking outcomes were calculated for each walking purpose: whether they reported any walking or not and whether or not a participant met physical activity recommendations of at least 150 minutes of physical activity in the last week (Centers for Disease Control and Prevention, 2016) or not through walking for each purpose. Thus, there are six walking outcomes: any walking for commuting; any walking for errands; any walking for exercise; sufficient walking for commuting; sufficient walking for errands; sufficient walking for exercise.

Sedentary behaviours. Participants reported their time spent TV viewing and car driving in the past week using a validated questionnaire (Ishii et al., 2013; Salmon et al., 2003). Two dichotomized sedentary behaviour outcomes were included: accumulating over two hours of TV viewing per day or not and accumulating over one hour of car driving per day. For TV viewing time, two hours per day was used as a cut-off based on its association with elevated health risks (Bowman, 2006; Dunstan et al., 2005). The cut-off of one hour per day was chosen for car driving based on its negative association with cardio-metabolic risk markers (Sugiyama et al., 2016).

Statistical Analysis

Logistic regression analyses were used to examine associations of Walk Score® with the walking and the sedentary behaviour measures. Models were adjusted for self-reported socio-demographic variables (age, gender, employment status, education attainment, marital status, and household income). All analyses were conducted using Stata 15.0 (Stata Corp, College Station, Texas), and the level of significance was set at $p < 0.05$.

5.1.3. Results

There were 1,076 survey respondents (response rate: 35.9%). After excluding those for whom Walk Score® was unavailable, data from 1,072 were analyzed (Figure 4). Table 4 shows the study sample's characteristics. Walk Score® ranged from 0 to 97. Table 5 shows the results of the regression analysis. Each 10-point increment in Walk Score® was associated with 34% higher odds of any walking for commuting; 6% higher odds of any walking for errands; 36% higher odds of sufficient walking for commuting; and 10% lower odds of driving a car for more than one hour per day. Walk Score® was not associated with walking for exercise, sufficient walking for commuting or sufficient walking for exercise, and TV viewing time.

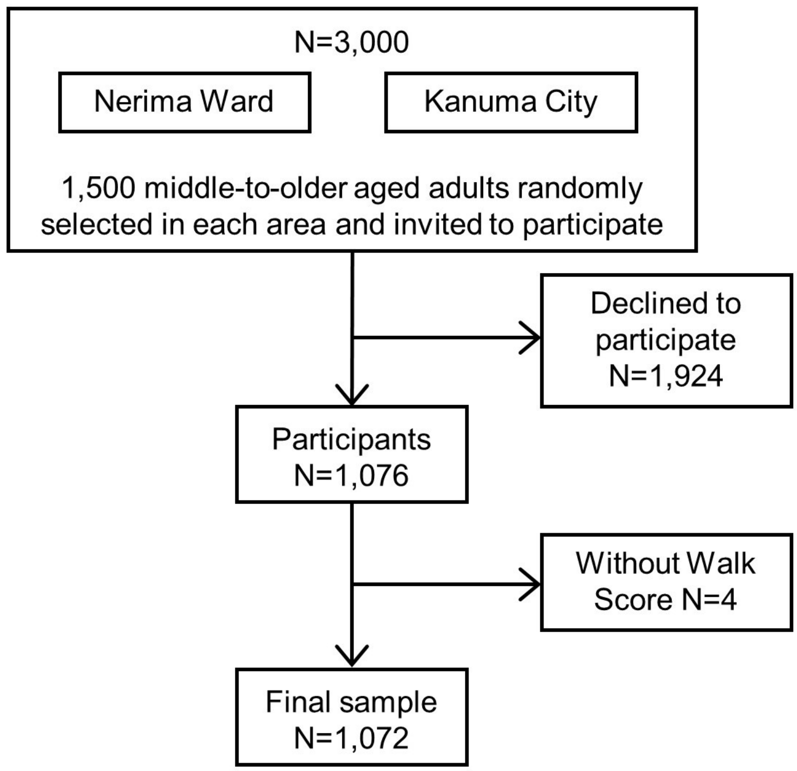


Figure 5. Recruitment and selection process

Table 4. Characteristics of study participants (N=1,072)

Variable	Mean (SD) or N (%)
Age (years)	55.6 (8.4)
Gender	
Women	518 (48.3)
Men	554 (51.7)
Employed	
Yes	780 (72.8)
No	283 (26.4)
Missing	9 (0.8)
Education	
Tertiary or higher	566 (52.8)
Below tertiary	505 (47.1)
Missing	1 (0.1)
Marital status	
Single	165 (15.4)
Couple	904 (84.3)
Unknown	3 (0.3)
Household income (per annum)	

<¥5,000,000	
≥¥5,000,000	530 (49.4)
Missing	521 (48.6)
	21 (2.0)
Any walking for commuting	400 (37.3)
Any walking for errand	530 (49.4)
Any walking for exercise	469 (43.8)
Sufficient [a] walking for commuting	158 (14.7)
Sufficient [a] walking for errands	97 (9.0)
Sufficient [a] walking for exercise	183 (17.1)
TV viewing ≥ 2 hr. per day	549 (51.2)
Car driving ≥ 1 hr. per day	88 (8.2)
Walk Score®	62.2 (27.5)

[a] ≥ 150 min of walking per week

Table 5. Associations of Walk Score® with purpose-specific walking and sedentary behaviours

	OR (95%CI)[a, b]
Any walking for commuting	1.34* (1.25, 1.42)
Any walking for errands	1.06* (1.01, 1.11)
Any walking for exercise	0.99 (0.95, 1.04)
Sufficient [c] walking for commuting	1.36* (1.23, 1.50)
Sufficient [c] walking for errands	1.08 (0.98, 1.19)
Sufficient [c] walking for exercise	1.02 (0.96, 1.09)
TV viewing ≥ 2 hr. per day	1.04 (0.99, 1.09)
Car driving ≥ 1 hr. per day	0.90* (0.83, 0.97)

[a] Odd ratios (ORs) correspond to a 10-point increment in Walk Score® (range: 0-97).

[b] Adjusted for age, gender, employment status, education attainment, marital status, and household income.

[c] ≥ 150 min of walking per week

* $p < 0.05$

5.1.4. Discussion

These findings provide original evidence that Walk Score® can be associated with physical activity and sedentary behaviour in a non-Western context. Using data from adults living in urban and rural areas in Japan, we found Walk Score® to be positively associated with transportation-related walking and sufficient walking for commuting. Previous studies in Western countries showed a higher Walk Score® to support walking for transport (Brown et al., 2013; Hirsch et al., 2013). Our study confirmed these findings in Japan, which has different environmental characteristics (e.g., population density, access to public transport) from North America or Australia (Kaido, 2006; Kenworthy and Laube, 2002). Similar to previous studies (Hirsch et al., 2014; Tuckel and Milczarski, 2015), we did not find a significant association between Walk Score® with leisure walking. Although Walk Score® considers access to recreational destinations such as parks, it is only a part of many other destinations. Walk Score® also does not assess the quality of recreational destinations, which was found to be related to leisure walking (Sugiyama et al., 2012b).

Our study also extended the previous research by showing the negative association between Walk Score® with car time. We found that areas with a higher Walk Score® are supportive of walking for transport and lower car use. Although many studies have examined associations of environmental attributes with physically-active behaviours, limited research has investigated how such attributes may be related to sedentary behaviours (Koohsari et al., 2015b). Our findings provide new evidence on the relevance of Walk Score® to car use, a typical sedentary behaviour among adults (Sugiyama et al., 2012a).

A practical implication of these findings is that Walk Score® can be used to identify areas where residents are likely to have active or sedentary lifestyles. Such knowledge, which can be obtained from a freely available tool, would help urban designers and local government officials to propose and implement measures to increase walking and decrease sedentary behaviours in less-walkable areas. Potential urban design initiatives to promote more-active lifestyles in urban areas can include land use changes to increase ease of access to destinations, mixed-use development, management of car parking, and enhancement of recreational facilities. In rural settings, where it is not practical to expect increases in shops and services to be viable, efforts may have to focus on increasing recreational activities. This study did not examine cycling, but it is a common transport mode in Japan, with several cities having started public bike-share programs (Nakamura and Abe, 2014). Cycling can be promoted in urban and rural areas, where one must travel a relatively long distance to reach local destinations. Considering that environmental factors conducive to cycling can be different from those facilitating walking (Van Dyck et al., 2012), a new environmental indicator targeting cycling may have to be developed.

There are some limitations in this study, including the use of self-reported walking and sedentary behaviours. There is also a temporal mismatch between data collection from participants (2011) and the extraction of Walk Score® (2016). Since Japan is a developed country in which rapid environmental changes are rather rare, local destinations are relatively stable over the short term. However, there may have been particular areas where destinations had changed substantially during the period. Historical Walk Score® data are needed to address this limitation. The strength of the study includes data collection from urban and rural areas. The multi-site data collection, which allowed us to examine broad variability in both the outcome and exposure measures, helps to characterize the relationships between them by including harder-to-capture values at the extremes at both ends of the relevant distributions. However, we cannot address whether the relationships may or may not be linear; their shape may differ in urban and rural areas. Future research is needed to identify a threshold (Koohsari et al., 2013; Sugiyama et al., 2012b) in Walk Score® above or below which the gradient may, for example, become flat or reversed.

5.2. Space syntax and active and sedentary behaviours

5.2.1. Introduction

Regular physical activity confers numerous health benefits, including reduced risk of chronic diseases such as type 2 diabetes, cardiovascular disease, obesity, and some cancers (Beaglehole et al., 2011). Sedentary behaviour—too much sitting— has also been identified as a distinct behaviour with adverse health consequences (Owen et al., 2010; Wijndaele and Healy, 2016). Despite public health efforts to promote active living, a more sedentary lifestyle (lack of physical activity and prolonged sitting) is prevalent in many countries. For example, the national household travel surveys found that less than 20% of US adults reported any walking (Pucher et al., 2011). In Japan, population-level physical activity has shown continued declines over the last few decades (Inoue et al., 2011). In addition, Japanese people spend a high proportion of their waking hours sitting. An international study with data from 20 countries found that adults in Japan reported the highest amount of sitting per day, with a median of over 360 min per day (Bauman et al., 2009).

Ecological models of physical activity and sedentary behaviours emphasize the importance of people's surrounding built environments in shaping their daily actions (Sallis and Owen, 2015). Over the past decade, a wide range of built environment attributes have been investigated in relation to physical activity, especially walking (Ewing and Cervero, 2010; Gebel et al., 2007; Saelens and Handy, 2008), which is an everyday physical activity of adults (Millward et al., 2014; Spinney et al., 2012). For example, many studies have found the walkability construct – which consists of residential density, land use mix, intersection density, and net retail area ratio – to be associated with several types of physical activity behaviours, mainly walking (Frank et al., 2005). In Japan, a few previous studies examine the relationships between population density and walking (Inoue et al., 2009; Inoue et al., 2010). Although these studies used self-reported density measures, their findings are consistent with studies in other countries (i.e., higher density is associated with more walking). On the other hand, mixed findings on the associations of perceived street connectivity with walking have been reported in one Japanese study (Inoue et al., 2010).

Street connectivity — the way streets are connected in a neighbourhood — has been consistently found to be related to active travel behaviours such as walking and bicycling (Koohsari et al., 2015b; Sugiyama et al., 2012b). Street connectivity appears to be a fundamental component of urban form, which can be measured relatively easily using the street centerline data typically available through local instrumentalities (Koohsari et al., 2016a). Further evidence, especially from Asian countries, on the association of street layout with walking behaviour should thus be particularly helpful for future research.

Compared with less-connected street layouts, well-connected street layouts are more conducive to active travel behaviours such as walking and bicycling, partly by providing more direct route options (Saelens et al., 2003b). For example, a study conducted in 24 Californian cities found higher street connectivity associated with more walking, cycling, and transit use (Marshall and Garrick, 2010). A recent international study on the association of built environment attributes with active travel behaviours also found well-connected street layouts associated with transport-related walking and cycling (Christiansen et al., 2016). It has also been found that more connected areas tend to have more local destinations (Koohsari et al., 2017b; Koohsari et al., 2016b). For example, a recent study found the association between street layout and walking partly mediated through local destination availability (Koohsari et al., 2016b).

Nevertheless, this area of research has been limited in two important ways. First, studies on street layout measures correlates of physical activities, and sedentary behaviours have been conducted predominantly in Western countries such as the United States, Australia, Canada, Belgium, and the United Kingdom. Little is known about these relationships in the context of non-Western countries. In Japan, a few studies have examined the relationships between built environment attributes and specific physically-active behaviours. These have mainly relied on self-report measures of neighbourhood attributes and did not include sedentary behaviours (Chen et al., 2013; Inoue et al., 2010). Two recent reviews on built environment attributes related to walking, and sedentary behaviours in adults have identified only two (out of 63) studies from Japan on these topics (Koohsari et al., 2015b; Sugiyama et al., 2012b). Japanese cities have different environmental attributes in comparison to Western cities. For example, the average population and building densities in Japanese urban areas are generally higher than in Western cities, and Japanese cities have better public transport accessibility (Kaido, 2006; Kenworthy and Laube, 2002). Because of these unique environmental characteristics, evidence on street layouts associated with active behaviours obtained in previous research may not be applicable to Japan. Previous studies have also shown that urban and rural areas might differ in how built environment attributes are related to active travel behaviours (Frost et al., 2010; Hansen et al., 2015; Millward and Spinney, 2011). Nevertheless, the majority of previous studies examining the associations of street layout with active travel behaviours have been conducted in urban or suburban settings. It is unknown how street layouts are related to active travel behaviours in rural areas.

This paper, therefore, has two aims: to examine to what extent street layout is associated with walking and sedentary behaviours in the context of Japan; and to examine whether associations of street layout with these behaviours differ between an urban and a rural area.

5.2.2. Methods

Data Source and Study Setting

This study used cross-sectional survey data from a part of the Healthy Built Environment in Japan (HEBEJ) project. The HEBEJ project, conducted at the Faculty of Sport Sciences, Waseda University, explores how the built environment may influence health behaviours and outcomes in Japan among middle-to-older adults. Middle-aged adults were included in this project because this is a life stage when people begin to experience age-related functional decline and other associated health problems (World Health Organization, 2002). Data were collected in 2011 from middle-to-older adult residents living in Nerima Ward (urban area) and Kanuma City (rural area). The recruitment procedure of the current study was guided by the method of the International Physical Activity and the Environment Network (IPEN) studies in which participants were recruited from high-walkable and low-walkable areas (Kerr et al., 2013). The main reason for this procedure is the larger variability in the relevant environmental measures (Giles-Corti et al., 2005). Nerima Ward is part of the Tokyo Metropolitan area with 716,000 residents and an area of 48 km^2. Kanuma City is a regional area located about 120 km north of Tokyo with 102,000 residents and 491 km^2. A total of 1,500 residents aged 40 to 69 years were randomly selected from the registry of residential addresses (balanced in gender and age group) from each city. The postal survey was completed by 1,076 participants (response rate: 36%). Written informed consent was obtained from all respondents. This survey and its linkage with built environment measures received prior approval from the Institutional Ethics Committee of Waseda University (2010-238).

Measures

Walking behaviours. Participants reported walking in the past week for three specific purposes: commuting, errands, and exercise (defined as at least 5 minutes of continuous activity). The validity of walking questions was reported elsewhere (Inoue et al., 2010). Six dichotomized walking outcomes were calculated for each participant: whether they reported any walking or not for each purpose and whether they met physical activity recommendations of at least 150 minutes of physical activity in the last week (Centers for Disease Control and Prevention, 2016) or not through walking for each purpose.

Sedentary behaviours. Using a validated questionnaire (Ishii et al., 2013; Salmon et al., 2003), participants were asked about time spent on TV viewing (TV viewing time did not include any other screen time) and car driving in the past week. Two dichotomized sedentary behaviour outcomes were calculated for each participant: accumulating over two hours of TV viewing per day, or not; and, accumulating over one hour of car driving per day, or not. The cut-off of two hours/day was chosen for TV viewing time on the basis of previous studies showing its health risks (Bowman, 2006; Dunstan et al., 2005). For car driving, we used one hour/day as a cut-off based on a recent study showing adverse associations of car use over 1 hr/day with markers of cardio-metabolic risk (Sugiyama et al., 2016).

Exposures

Street layout measures. Two street layout measures —intersection density and street integration— were examined. Although related, these two street layout measures can have distinct associations with walking behaviour (Koohsari et al., 2016b). Intersection density was calculated using GIS as the total number of three-way or more intersections per hectare within an 800-meter radius buffer of participants' geocoded residential address. An 800-meter radius buffer was selected to be consistent with previous studies examining environmental correlates of active behaviour among middle-to-older adults (Nagel et al., 2008; Troped et al., 2014). Street integration, a key measure in space syntax, refers to how a street segment is 'topologically' close to other street segments within the network (Hillier, 2009). Compared with less-integrated segments, more integrated street segments require fewer turns to reach them from the other street segments and thus are considered to be more accessible (Hillier, 2009; Kostakos, 2010; Peponis and Wineman, 2002). Details of methods to calculate street integration have been reported elsewhere (Koohsari et al., 2016b). Briefly, using Axwoman (Jiang, 2012) and University College London DepthMap (Turner, 2004) software, an integration score was calculated for each street segment considering all the other street segments within a 1 km distance from its centre. Then, the mean integration score was calculated for each participant within a 1 km radius buffer of their geocoded residential address. The 1km was chosen based on previous space syntax studies showing the high correlation between street layout and pedestrian flow in this scale (Hillier and Iida, 2005; Lerman et al., 2014), and the two-level aggregation method to assign a street integration measure to each participant is consistent with previous studies on space syntax and walking (Koohsari et al., 2016b; Wineman et al., 2014).

Covariates: Socio-demographic variables. The following socio-demographic characteristics were reported by participants: age, gender, employment status, educational attainment, marital status, and household income.

Statistical Analysis

Logistic regression analyses were used to examine associations of street layout with purpose-specific walking and sedentary behaviours. The regression models were adjusted for socio-demographic variables (age, gender, employment status, education attainment, marital status, and household income). Each street layout measure was included separately in each model. We did not adjust for the areas of residence when the total sample was analyzed because they represented high connectivity (urban) and low connectivity (rural) areas. The interaction between the areas of residence and each exposure measure was also examined. Stratified analyses were conducted when the interaction term approached significance ($p \approx 0.1$). Analyses were conducted using Stata 14.0 (Stata Corp, College Station, Texas).

5.2.3. Results

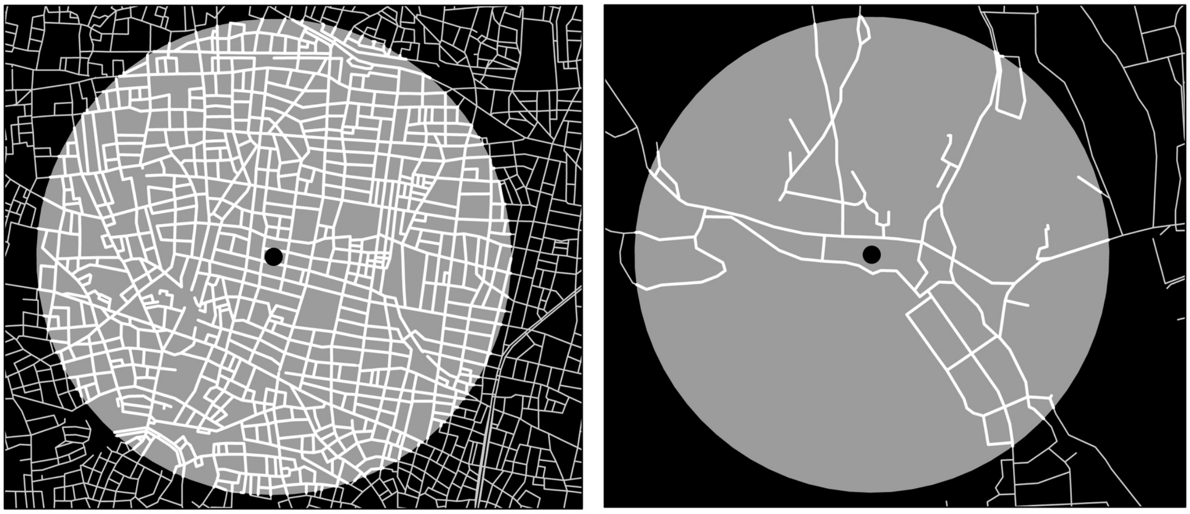
Table 6 shows the characteristics of the study sample. There was a significant difference between the mean street integration measures between the urban and the rural city. Figure 5 shows an example of street layout in Nerima Ward and Kanuma City. Intersection density and street integration were highly correlated ($r = 0.85$).

Table 6. Characteristics of study participants (N=1,076)

Variable	**N (%)**		
	Total sample	**Nerima Ward (n=569)**	**Kanuma city (n= 507)**
Age [Mean (SD)]	55.5 (8.4)	55.8 (8.5)	55.3 (8.3)
Gender			
Women	520 (48.3)	283 (49.7)	237 (46.7)
Employed			
Yes	784 (73.5)	413 (72.6)	371 (73.2)
Education			
Tertiary or higher	568 (52.8)	384 (67.5)	184 (36.3)
Marital status			
Single	167 (15.5)	90 (15.8)	77 (15.2)
Couple	906 (84.2)	478 (84.0)	428 (84.4)
Unknown	3 (0.3)	1 (0.2)	2 (0.4)
Household income (per annum)			

<¥5,000,000	533 (49.5)	254 (44.6)	279 (55.0)
≥¥5,000,000	522 (48.5)	302 (53.1)	220 (43.4)
Missing	21 (2.0)	13 (2.3)	8 (1.6)
Any walking for commuting	400 (37.2)	296 (52.0)	104 (20.5)
Met physical activity recommendations[a] by walking for commuting	158 (14.7)	137 (24.1)	21 (4.1)
Any walking for errands	531 (49.3)	322 (56.6)	209 (41.2)
Met physical activity recommendations by walking for errands	97 (9.0)	59 (10.4)	38 (7.5)
Any walking for exercise	470 (43.7)	248 (43.6)	222 (43.8)
Met physical activity recommendations by walking for exercise	184 (17.1)	101 (17.8)	83 (16.4)
TV viewing ≥ 2 hr. per day	552 (51.3)	277 (48.7)	275 (54.2)
Car driving ≥ 1 hr. per day	88 (8.2)	28 (4.9)	60 (11.8)
Intersection density [Mean (SD)]	3.5 (2.3)	5.5 (0.8)	1.26 (0.9)
Street integration [Mean (SD)]	954.6 (785.8)	1592.7 (529.9)	234.1 (135.7)

[a] ≥ 150 min of walking per week



(a)
Intersection density= 287
Street integration= 1195

(b)
Intersection density= 12
Street integration= 81

Figure 6. Examples of street layout in (a) Nerima Ward and (b) Kanuma City

Table 7 shows the results of the regression analyses for purpose-specific walking and sedentary behaviours for the total sample and stratified analyses by the areas of residence when the interaction was significant. For intersection density, a one intersection increase per hectare was associated with 48% higher odds of any walking for commuting; 56% higher odds of meeting physical activity recommendations through walking for commuting; 13% higher odds of any walking for errands; and 16% lower odds of driving a car more than one hour per day. Similarly, each 100-point increment in street integration score was associated significantly with 10% higher odds of any walking for commuting; 10% higher odds of meeting physical activity recommendations through walking for commuting; 4% higher odds of any walking for errands; and a 5% lower odds of driving a car more than one hour per day. Walking for exercise, TV viewing time, and meeting physical activity recommendations through walking for errands or walking for exercise were not associated with street layout measures for the total sample.

The interaction between the areas of residence and intersection density on walking for errands and TV viewing were statistically significant ($p = 0.05$ and $p = 0.10$, respectively). Walking for errands was significantly positively associated with intersection density in Nerima Ward (urban area) but not in Kanuma City (rural area). However, TV viewing time was significantly positively associated with intersection density only in Kanuma City (a rural area). The interaction between the areas of residence and street integration was also significant for walking for commuting ($p = 0.03$) and TV viewing ($p = 0.01$). Walking for commuting and TV viewing were significantly positively associated with street integration in Kanuma City but not in Nerima Ward.

Table 7. Associations of street layout measures with purpose-specific walking and sedentary behaviours

	OR[a] (95%CI)					
	Intersection density			Street integration		
	Total sample	Nerima Ward (urban)	Kanuma City (rural)	Total sample	Nerima Ward (urban)	Kanuma City (rural)
Any walking for commuting	**1.48**[c] (1.37, 1.59)	-	-	**1.10** (1.08, 1.12)	0.99 (0.95, 1.03)	**1.21** (1.02, 1.43)
Met physical activity recommendations[b] by walking for commuting	**1.56** (1.40, 1.73)	-	-	**1.10** (1.07, 1.12)	-	-
Any walking for errands	**1.13** (1.07, 1.20)	**1.24** (1.00, 1.55)	0.89 (0.72, 1.10)	**1.04** (1.02, 1.05)	-	-
Met physical activity recommendations by walking for errands	1.05 (0.94, 1.16)	-	-	1.00 (0.97, 1.03)	-	-
Any walking for exercise	0.97 (0.92, 1.03)	-	-	1.00 (0.98, 1.01)	-	-
Met physical activity recommendations by walking for exercise	1.02 (0.94, 1.10)	-	-	1.00 (0.98, 1.02)	-	-
TV viewing ≥ 2 hr. per day	0.99 (0.94, 1.05)	1.12 (0.90, 1.39)	**1.47** (1.18, 1.83)	0.99 (0.97, 1.01)	1.00 (0.96, 1.03)	**1.22** (1.06, 1.41)
Car driving ≥ 1 hr. per day	**0.84** (0.76, 0.93)	-	-	**0.95** (0.92, 0.98)	-	-

All models adjusted for age, gender, employment status, educational attainment, marital status, and household income.
[a] Odd ratios (ORs) correspond to a 100-point increment in street integration (range: 17-2973). [b] ≥ 150 min of walking per week [c] Bold figures are significant ($p < 0.05$); Results of stratified analyses were shown only when the interaction was significant ($p \approx 0.1$

5.2.4. Discussion

This is the first study to examine the associations of objectively-measured street layout measures with walking and sedentary behaviours in an Asian country context. We found that well-connected street layout was associated with more transportation-related walking (any for commuting and for errands, and meeting physical activity recommendation through walking for commuting). These findings differ from the only previous study conducted in Japan, which found no associations of street connectivity with total walking or habitual exercise (Chen et al., 2013). However, they used a perceived measure of street connectivity, rather than an objective measure. Perceptions of street connectivity do not always match with the objective measures of street layout (Koohsari et al., 2015a). Our findings are consistent with previous studies conducted in Western countries that have shown objectively-assessed street connectivity to be supportive of physical activity behaviours (Badland et al., 2008; Marshall and Garrick, 2010; Sarkar et al., 2015). Our study confirmed that street layout is also relevant to walking for transport in Japan, and extended previous findings showing street layout is also associated with meeting physical activity recommendation through walking for commuting. It has been suggested that local commercial destinations tend to exist in areas with more-connected streets (Koohsari et al., 2016b), and this may be a reason for more walking for errands.

We found no association between street layout and walking for exercise. This is consistent with evidence showing the importance of recreational destinations and aesthetics for recreational walking compared with street connectivity (Sugiyama et al., 2012b). In addition, similar with a recent study conducted in Australia (Koohsari et al., 2017b), participants who were living in more connected areas were less likely to drive more than one hour per day. It is possible that areas with high street connectivity may not require a car for daily travel, or car use may not be easy in such areas due to difficulty in parking. These findings support the emerging evidence showing the relevance of street layout to transport-related sedentary behaviours (Koohsari et al., 2015b). High street connectivity can be important for community health, as residents in such areas are likely to engage not only in more walking but also in less driving.

Our findings suggest that the effects of street layout measures on walking and sedentary behaviours may differ between urban and rural areas. We found intersection density to be associated with walking for errands in urban areas, while street integration found to be associated with walking for commuting in rural areas. The exact reasons for these findings are unknown. But, one potential reason for these different associations of street layout measures on walking between urban and rural areas may be possible nonlinear relationships between built environment attributes and walking (Stewart et al., 2016). In our study, street layout measures were significantly higher in urban and lower in rural areas, and there may be an optimum level above which each street layout measure is not positively associated with walking behaviour. For example, a recent international study found 200-250 intersections per square kilometer to be an optimal level for walking for transport (Christiansen et al., 2016). However, the maximum intersection density in their study was about 400 intersections per square kilometer (Adams et al., 2014b), which is smaller than what we had in our study (731 intersections per square kilometer). It is possible that street integration in Kanuma City may be very high overall, and higher integration may have little impact on walking. Further research in the context of Asian cities may be able to identify the 'optimal levels' of street connectivity to facilitate active travel behaviours. However, this does not explain other urban-rural differences (e.g., significant association of intersection density with walking for errands only in Nerima Ward). Walking for commuting and for errands in these areas may be determined by different factors (e.g., lack of places to shop nearby in the rural area), which requires further research to fully understand. It is notable that there were more significant associations for the whole sample compared with the stratified sample. This may be partly because of larger variance in street layout measures by combining urban and rural areas. This suggests that simply looking at one location may not provide enough variance in the built environment exposure measure in relation to active behaviours (Giles-Corti et al., 2005). In the rural area, street connectivity was also positively associated with TV viewing time. It is unknown why those living in high-connected areas watched TV longer than those in low-connected areas in Kanuma City. But, participants in these areas may engage in different occupations: clerical/manufacturing work in central areas, agricultural/farming work in remote areas. Difference in TV time may be a reflection of different lifestyles of these occupations.

This study used a cross-sectional design, and self-reported walking and sedentary behaviour measures that may be subject to recall and social-desirability biases (Rizzo et al., 2007; van der Ploeg et al., 2010). Further longitudinal research using objectively-measured behaviour outcomes are necessary to confirm these results. In addition, all streets including those inaccessible for pedestrians' were included in this study, and only one buffer size was employed to aggregate each street layout measure. Future studies can use 'pedestrian network' and a variety of buffer sizes in calculating the street network measures.

5.3. Space syntax walkability

Evidence demonstrating the negative health consequences of sedentary behaviour (too much sitting), after adjusting for physical activity is accumulating (Chastin et al., 2015). Sitting for many individuals is a habitual behaviour which is undertaken in large doses daily (e.g., television and computer use, car driving). For example, Canadian adults spend at least two-thirds of their waking time in sedentary behaviours (Colley et al., 2011). To reduce sedentary behaviour, interventions that incorporate individual, social, and built environment level factors are needed (Owen et al., 2011). In particular, built environment attributes are barriers or facilitators for physical activities and may be relevant to sedentary behaviours. Nevertheless, a recent systematic review reported only mixed evidence on the associations between built environment attributes and adults' sedentary behaviours – less than 30% of associations were in the expected direction (Koohsari et al., 2015b). Furthermore, few studies have examined associations between built environment attributes (especially objectively-measured attributes) and sedentary behaviours in different geographical locations. Only 17 papers were included in the systematic review on the built environment attributes and adults' sedentary behaviours, none of which were from Canada (Koohsari et al., 2015b). In a recent systematic review on correlates of adults' sedentary behaviour, less than 20% of 257 eligible studies examined built environment attributes, which included only two Canadian studies (Prince et al., 2017). Thus, more evidence on the associations between the built environment and sedentary behaviour in different geographical locations is needed to inform local urban design policy and public health interventions.

Furthermore, it is important that objective measures of built environment have practical interpretation, can be estimated for different contexts, and can be constructed using readily available data. It is of interest to examine a newly-developed built environment index, space syntax walkability (SSW), in relation with sedentary behaviours. The details of SSW have been fully described elsewhere (Koohsari et al., 2016a). Briefly, SSW includes two measures of neighbourhood population density and street integration. While SSW employs readily-available spatial geographical data, compared with the conventional neighbourhood walkability index (Frank et al., 2010); both indices were found to be equally associated with walking for transport (Koohsari et al., 2016a). Few studies have examined the associations between space syntax metrics and health behaviours and outcomes (Baran et al., 2008; Koohsari et al., 2018a; Koohsari et al., 2017b), and notably, none have explored the associations between SSW and sedentary behaviours.

Therefore, the aim of this study was to examine the associations of objectively-measured built environment attributes and a composite measure of SSW with two common sedentary behaviours (i.e., leisure screen time and car driving) in a sample of Canadian adults.

5.3.2. Methods

Data source and participants

Detailed methods of study design and recruitment have been documented elsewhere (McCormack et al., 2010). Briefly, a random sample of adults (≥18 years of age) was recruited for telephone-interviews during August-October 2007 (n=2199, response rate=33.6%) and January-April 2008 (n=2223, response rate=36.7%). Telephone-interviews captured information about sociodemographic characteristics and physical activity. Of participants who completed the telephone-interview, 2006 participants completed and returned a follow-up postal survey. Sedentary behaviour and additional sociodemographic characteristics were obtained by the postal survey. The University of Calgary Conjoint Health Research Ethics Board approved this study (REB# 20798).

Measures

Outcome variable. The outcome variables were self-report leisure screen time and car driving and have been fully-described previously (McCormack and Mardinger, 2015; Swanson and McCormack, 2012). The former was measured by the following question:

"On average, how many hours per week do you spend watching television or using a computer outside of your workplace? (e.g., videogames, computer games, DVD/movies, internet, email, etc.)". Participants also reported the total time on a typical weekday and weekend day spent as a driver or passenger travelling in a car. Total weekly driving time was calculated by summing weekday (multiplied by 5) and weekend (multiplied by 2) driving time.

Built environment attributes. Participants were geocoded using their 6-digit residential postal codes. Using GIS, population density, intersection density, availability of sidewalks, and availability of destinations were objectively calculated within a 1.6 km network buffer around each participant's geocoded point. The choice of 1.6 km buffer was similar to previous studies examining associations between built environment and health behaviours (Christian et al., 2011). All businesses in City of Calgary were coded according to their primary type of service (restaurants, bakeries, convenience stores, cinemas, drugstores, supermarkets, etc.). These addresses were geocoded and the total number of businesses within each participants' buffer were calculated. Informed by a previous study (Koohsari et al., 2016a), the SSW index was calculated as a composite measure including population density and street integration. Street integration was calculated for each street segment considering all the other street segments within a 1.6 km distance from its centre using Axwomen and Depthmap software (Jiang, 2012; Turner, 2004). SSW was calculated using the following formula (Koohsari et al., 2016a):

SSW = z [z (population density) + 2×z (integration)].

Socio-demographic variables. Participants were reported their age, gender (female, male), education (high school or less, college, university), annual gross household income (<$60 000/year, $60 000–119 999/year, ≥$120 000/year, don't know/refused), marital status (married/living together, single/divorced/separated), number of children <18 years of age at home (no child, at least one child), and self-rated health (poor/fair, good, very good, excellent).

Statistical analysis

Descriptive statistics (mean ± standard deviation; frequencies) were estimated for the sample. Generalized linear models (gamma distribution with identity link function) were used to estimate the associations between the built environment attributes and SSW with leisure screen and driving time, adjusting for the socio-demographic variables. Additionally, the same results hold when we controlled for seasonality. Each built environment attribute was examined separately in each model (not mutually adjusted) to examine their total effects. Analyses were conducted using Stata 15.0 (Stata Corp, College Station, Texas), and the level of significance was set at $p < 0.05$.

5.3.3. Results

Complete data from 1904 participants were included in this analysis. The mean age was 50.7 years, and about two-thirds (62.8%) were female, about 45% had completed a university degree, approximately 30% had an annual gross household income lower than \$60 000/year, about 70% were married or living together, just about two-thirds (66.5) had no children at home <18 years of age, and approximately 44% reported very good or excellent health status (Table 8). Participants reported an average of 12.6 and 9.8 hours/week leisure screen time and car driving, respectively.

Table 8. Characteristics of study participants (N= 1904)

Variable	Mean (SD) or N (%)
Age (mean)	50.7 (15.4)
Gender	
Female	1195 (62.8)
Men	709 (37.2)
Education	
High school or less	572 (30.0)
College	488 (25.6)
University	844 (44.3)
Annual gross household income	
<\$60 000/year	572 (30.0)
\$60 000–119 999/year	612 (32.1)
≥\$120 000/year	554 (29.1)
Don't know/refused	166 (8.7)
Marital status	
Married/living together	1316 (69.1)
Single/divorced/separated	588 (30.9)

Children at home <18 years of age	
No child	1267 (66.5)
At least one child	637 (33.5)
Self-rated health	
Poor/fair	287 (15.1)
Good	781 (41.0)
Very good	640 (33.6)
Excellent	196 (10.3)
Leisure screen time (hours/week)	12.6 (10.6)
Car driving (hours/week)	9.8 (10.2)

Adjusting for covariates, a one standard deviation increase in SSW was associated with a 0.43 (95% CI -0.85, -0.02) hours/week decrease in leisure screen time (Table 9). None of the other built environment attributes were significantly associated with leisure screen time. Adjusting for covariates, all built environment attributes (except the availability of sidewalks) were negatively associated with car driving (Table 9). The strongest association was observed between SSW and car driving – a one standard deviation increase in SSW was associated with 0.77 (95% CI -0.85, -0.02) hours/week decrease in the car driving.

Table 9. Associations between built environment attributes and leisure screen time and car driving (hours/week)

Built environment attributes	Leisure screen time	Car driving
	β (95% CI)	β (95% CI)
Population density	-0.34 (-0.75, 0.07)	-0.48 (-0.87, -0.10)*
Intersection density	-0.29 (-0.73, 0.14)	-0.51 (-0.96, -0.07)*
Availability of sidewalks	-0.21 (-0.66, 0.23)	-0.34 (-0.75, 0.07)

Availability of destinations	-0.31 (-0.74, 0.12)	-0.75 (-1.02, -0.49)*
Space syntax walkability	-0.43 (-0.85, -0.02)*	-0.77 (-1.20, -0.33)*

Note: β = regression coefficients for standardised environmental variables; CI= confidence interval; All models adjusted for age, gender, education, income, marital status, children at home, and self-rated health. * $p < 0.05$

Each built environment attribute was examined separately in each model.

5.3.4. Discussion

This study examined associations of built environment attributes and SSW with two common sedentary behaviours, leisure screen time and car driving, among a sample of Canadian adults. Consistent with some previous studies (Fields et al., 2013; Koohsari et al., 2017c), we found no significant associations between objectively-measured built environment attributes such as population density and street connectivity with leisure screen time. Nevertheless, a previous study conducted on the same dataset used in our study found that participants from neighbourhoods with higher population density, larger walkshed area, more path/cycleway availability, mix of recreational destinations, more business destinations, and bus stops (i.e., high walkability) reported less leisure screen time than those in less walkable neighbourhoods (McCormack and Mardinger, 2015). Another study conducted in Australia found that a composite measure of neighbourhood walkability including dwelling density, intersection density, land use mix, and net retail area was negatively associated with women's television viewing time (Sugiyama et al., 2007). These indicate that the combined effects of built environment attributes on sedentary behaviours may be different than their individual effects. Notably, examining the effects of individual built environment attributes on sedentary behaviour is still useful for providing an evidence-base for urban designers and policy-makers. In contrast with leisure screen time, car driving was found to be significantly associated with built environment attributes: those who lived in highly populated and more connected areas with a variety of destinations nearby were less likely to report car driving. A study conducted in Japan found that objectively-measured environmental attributes including population density, destinations, street connectivity, sidewalks, and access to public transportation to be associated with lower transportation sitting time (Liao et al., 2016). Another study in Australia also found that living in less connected areas to be associated with higher time spent in cars (Koohsari et al., 2017b). These findings provided further evidence on the importance of built environment attributes on two types of highly-common sedentary behaviours.

This is the first study, to our knowledge, examining associations between newly-developed SSW and sedentary behaviours. SSW was found to be significantly associated with both leisure screen time and car driving: those who lived in higher SSW areas reported less time engaged in leisure screen and driving sedentary activities. Importantly, SSW can be calculated without the need for detailed parcel land-use data, which are often either unavailable or difficult to obtain (Adams et al., 2014b). Therefore, the SSW can be estimated for different geographical locations, meaning that associations between the built environment and sedentary behaviours, as well as physical activities, can potentially be directly compared between cities and countries and across studies. Our findings underscore the relevance of SSW for sedentary behaviours. Future longitudinal studies are needed to confirm these findings and to expand them into different contexts and sedentary behaviours.

This study has limitations. Although self-reports provide reliable estimates of sedentary behaviour (Clark et al., 2009), they may still be subject to recall bias. Despite our measure of screen time capturing behaviour undertaken outside of the workplace, neither measure, screen time nor driving time, provided context-specific information about where the behaviours occurred. As a cross-sectional study, causal relationships cannot be inferred. Additionally, increased car driving may also be related to the location of neighbourhoods within Calgary – the more walkable neighbourhoods tend to be closer to the city core and less walkable on the periphery (McCormack et al., 2012). Furthermore, only one geographical buffer was used in this study to calculate built environment attributes. Future studies need to test how built environment attributes calculated within different geographical buffer sizes may influence sedentary behaviours.

5.4. Space syntax and cardiometabolic risk factors

5.4.1. Introduction

Non-communicable diseases such as cardiovascular disease, cancer, diabetes, and chronic respiratory diseases are the leading causes of death worldwide, accounting for 74% of all deaths in 2019 (World Health Organization, 2020). Despite temporal trends over the past two decades suggesting a plateauing or reduction in cardiovascular disease burden (e.g., disability-adjusted life years, mortality, and years of life lost) (Chen et al., 2018; Vos et al., 2020), cardiovascular disease remains in the two highest-ranked leading causes of non-communicable disease burden and death in North America (Kassebaum et al., 2016; Vos et al., 2020). Modifiable cardio-metabolic risk factors, such as overweight and obesity, hypertension, hyperglycemia, and lipid abnormalities, which lead to the majority of non-communicable diseases, are prevalent in many countries (World Health Organization, 2021). For example, over 25% of adults in Canada are obese (body mass index, BMI ≥30kg/m2) or hypertensive, almost 20% have elevated blood cholesterol, and approximately 7% have elevated blood glucose (Public Health Agency of Canada, 2019). Therefore, population-level interventions that prevent or decrease these cardio-metabolic risk factors are needed to reduce the significant health and economic burden of treating and managing non-communicable diseases, particularly cardiovascular disease (Foy and Mandrola, 2018).

There is potential to support population-wide changes in cardio-metabolic risk factors via implementing universal interventions such as creating health-supportive built environments (Prüss-Ustün et al., 2019; World Health Organization, 2017a). Improving cardio-metabolic clinical risk factors via modifying the built environment is vital for disease prevention (e.g., cardiovascular disease and diabetes). The premise of focusing on the built environment is that environmental changes may enable many people to make daily choices easy and healthy choices via structural features that persist over the long term (Chokshi and Farley, 2014; Gostin, 2014). Neighbourhood built environment characteristics such as pedestrian and street network connectivity, land use and destination diversity, population and residential density, greenspace, and walkability appear to be important for supporting cardio-metabolic health, particularly via their positive association with physical activity (Hajna et al., 2015; Kärmeniemi et al., 2018; Koohsari et al., 2020a; Koohsari et al., 2021b). For instance, a systematic review of 131 studies in 2011 examining environmental factors associated with cardio-metabolic risk factors found several walkable built environment characteristics such as higher intersection density, increased level of urbanisation, and higher residential density were negatively associated with obesity or hypertension (Leal and Chaix, 2011). Another meta-analysis in 2018 found that higher levels of neighbourhood walkability and green spaces, but not the food environment, were associated with a lower risk of type 2 diabetes (Den Braver et al., 2018).

While promising, much of the previous evidence examining links between the built environment and cardio-metabolic risk factors has been based on US studies. Relatively, fewer studies have investigated associations between urban form and cardio-metabolic risk factors in the Canadian context (McCormack et al., 2019). Findings from different geographical contexts may lack generalizability to the local context due to geo-climatic, healthcare systems, and political and cultural differences between countries. While Canada may be similar to other Western developed countries in terms of its prevalence, incidence, and burden of cardiovascular disease and cardio-metabolic risk factors, the intervention approaches needed to address these health issues likely need to reflect context nuances, including historical and contemporary differences in urban design and the built environment.

Moreover, many studies investigating the built environment and cardio-metabolic risk factors have relied on aggregated or composite built environment indices such as neighbourhood walkability and Walk Score® to estimate walking-friendly built environments (Braun et al., 2016a; Braun et al., 2016b; Coffee et al., 2013; Loo et al., 2017; Méline et al., 2017; Müller-Riemenschneider et al., 2013). While demonstrating predictive validity, these composite built environment indices are often limited in that they cannot always be easily translated into a form that can inform urban design and planning policy or practice. However, other approaches to creating composite built environment indices exist that are translatable for urban planners (e.g., based on the space syntax theory) (Koohsari et al., 2016a) and may better support decision-making in the design and building of health-supportive neighbourhoods.

Therefore, the current study estimated the associations between traditional and novel neighbourhood built environment metrics and clinically-assessed cardio-metabolic risk factors among a sample of adults in Canada. We stratified the analysis by sex, following previous studies that have shown some differences in associations of the built environment and cardio-metabolic risk factors for men and women (Müller-Riemenschneider et al., 2013; Tarlov et al., 2020; Wasfi et al., 2016).

5.4.2. Methods

Design and sample

This study included secondary analysis of an existing province-wide cohort dataset from Alberta's Tomorrow Project (ATP) conducted in Alberta, Canada (Figure 6). The methods of this cohort study have been presented in detail elsewhere (Robson et al., 2016; Ye et al., 2017). Briefly, from 2000-2008, a random sample (random digit dialling) of Albertan adults 35-69 years with no personal history of cancer and with no intention of leaving Alberta in the following year were invited to participate in the first wave of recruitment for ATP (n=63,486) and were enrolled upon providing informed consent and completing a health and lifestyle survey (n= 31,072). Participants recruited between 2000 and 2007 were invited to complete a follow-up health and lifestyle survey in 2008 (n= 20,707). From 2009-2015, ATP entered the second wave of recruitment, this time inviting new and existing participants to attend a study center for the collection of physical measures (e.g. height, weight, blood pressure) and biosamples (blood and urine) for biobanking and use in future research. This study involves cross-sectional analysis of data from participants enrolled in ATP who completed the 2008 health and lifestyle follow-up survey, had physical measures assessed, provided biosamples, and resided in urban areas (n=7171). The University of Calgary Conjoint Health Research Ethics Board approved this analysis (REB19-1992).

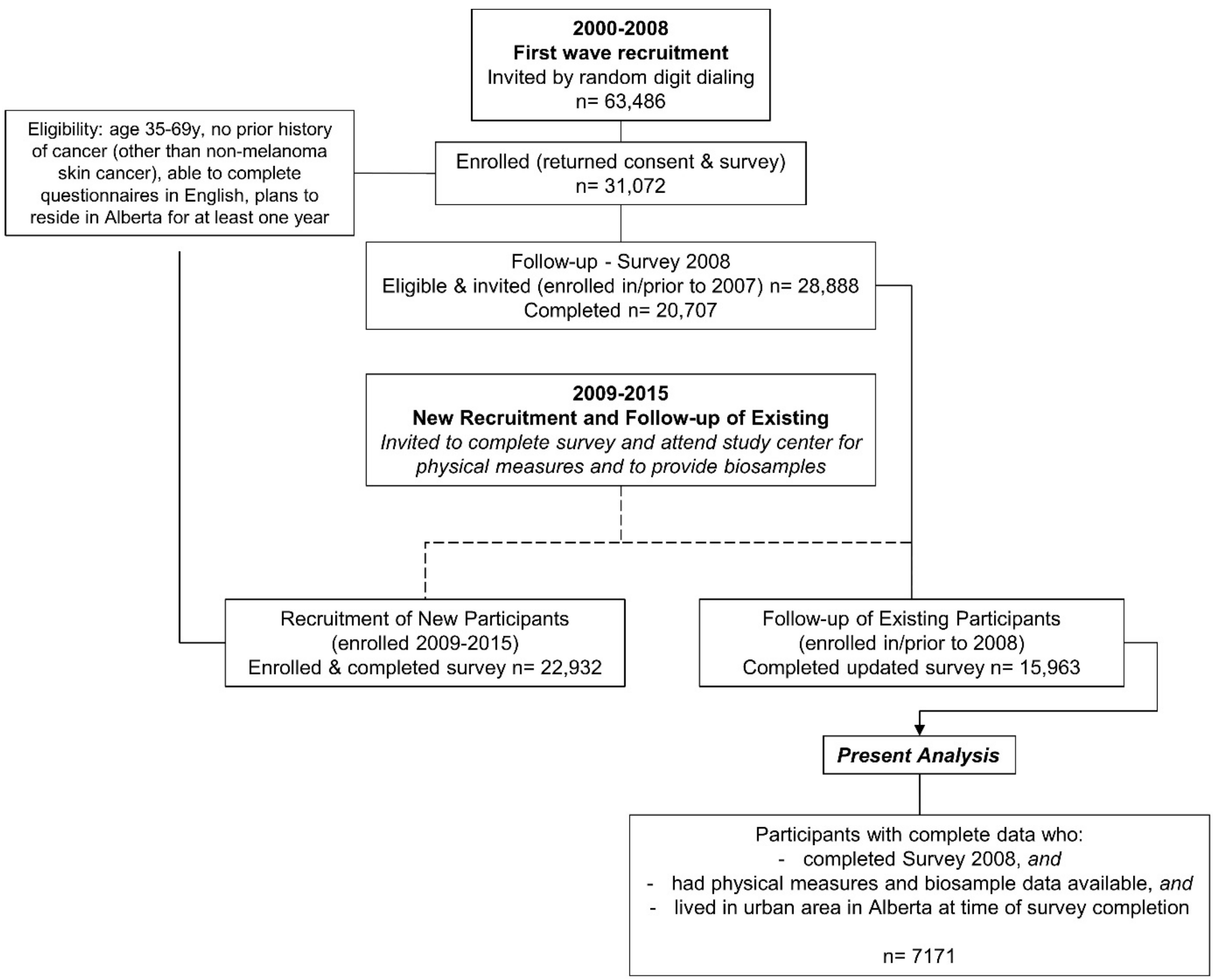


Figure 7. Participants' recruitment process

Health and Lifestyle Survey

The Health and Lifestyle Survey (Survey 2008) included a comprehensive questionnaire that captured information about sociodemographic characteristics, health history, cancer screening, primary care services use, quality of health, women reproductive health, perceived environmental characteristics, occupation, and health behaviours (i.e., sleep, smoking and tobacco use, diet, physical activity, and sedentary behaviour). We included sociodemographic characteristics from this survey comprising sex, age, marital status, highest education level, ethnicity, employment status, current smoking status, and annual household income. Excluding sex, which was used to stratify our analysis, all other sociodemographic variables were included as covariates in our analysis. We did not include health behaviours and other factors as covariates because the focus of our study was on estimating the total effect of the neighbourhood environment on cardio-metabolic risk factors.

Physical Measures and Biosample Data

Between 2009 and 2015, participants were invited to attend a study center where trained ATP staff measured anthropometrics (including sitting and standing height and weight) as well as blood pressure (Ye et al., 2017). Systolic and diastolic blood pressure were measured using the Omron® HEM907XL IntelliSense Automated Professional Digital Blood Pressure Monitor (Omron; Kyoto, Japan). The participant rested in a seated position for 5-minutes before the first blood pressure measurement, and staff took two more measurements 2-minutes apart to determine average blood pressure. A stadiometer (Seca 214/217) measured sitting or standing height (stretched stature) with shoes and head accessories removed. Weight was measured using the Tanita TBF-310 total body composition analyzer (Tanita; Tokyo, Japan). Body mass index (BMI; kg/m2) was calculated from the measured height and weight.

Blood samples (50 mL) were collected from participants in the non-fasting state into the red top, serum separator tube, and EDTA Vacutainers, processed via centrifugation, and then divided into aliquots of plasma, serum, buffy coat, and red blood cells and frozen in cryovials at-80°C (majority within 2h of collection, some within up to 24h of collection). Mid-stream spot urine samples were also collected from participants at the study center in sterile urine collection cups, aliquoted into cryovials, and frozen at-80°C. All samples were transported to the Alberta Cancer Research Biobank for longer-term storage in -80°C freezers. From 2017-2020, ATP pulled serum, red blood cell, and urine samples from the biobank for all participants (~30,000) who provided biosamples and send them to a clinical diagnostic lab (Calgary Lab Services, Calgary, Alberta) for analysis of a panel of clinical markers, including lipid panel (total and high-density lipoprotein (HDL)-cholesterol and triglycerides measured using enzymatic colorimetric assays; low-density lipoprotein (LDL)-cholesterol calculated via the Friedewald equation (Friedewald et al., 1972) and glycated hemoglobin A1c (HbA1c; measured by immunoturbidimetric assay).

Cardio-metabolic risk indicators (LDL-cholesterol, HDL-cholesterol, triglycerides, systolic and diastolic blood pressure, HbA1c, and BMI) were initially examined as continuous variables and then using clinical risk-related cut-points to establish risk levels. LDL-cholesterol was categorised into elevated LDL-cholesterol (≥ 3.37 mmol/L) versus optimal/near-optimal (American College of Sports Medicine, 2013). The threshold for at-risk HDL-cholesterol level was <1.04 mmol/L (American College of Sports Medicine, 2013). Triglycerides level was dichotomised to above borderline high triglycerides (≥ 1.70 mmol/L) versus normal (American College of Sports Medicine, 2013). Raised blood pressure was defined as systolic ≥140 or diastolic ≥90 (Observatory, 2021). Participants were considered to have elevated HbA1c if the measured HbA1c was ≥6.5% (Punthakee et al., 2018). The BMI cut-off value of 25 kg/m2 was used to dichotomise participants as overweight (including obese) versus normal weight (World Health Organization, 2016).

Neighbourhood Built Environment Metrics

Two composite built indices of traditional walkability and space syntax walkability were included in this study. Similar to previous studies (Carlson et al., 2016; Christoforou, 2011), the traditional walkability index calculated as the sum of the z-scores of population count, 3-way intersection, 4-way intersection, and business destinations: Traditional walkability = [z(population count) + z(3-way intersection) + z(4-way intersection) + z(business destinations)]. In pilot testing, the traditional walkability index and its components were positively correlated with the validated publically available Walk Score®

index (Pearson's r: traditional walkability=0.61; population count=0.35; 3-way intersections=0.10; 4-way intersections=0.49; business destinations=0.65; based on n=80,975 Alberta postal codes) (Carr et al., 2010; Duncan et al., 2011).

ArcGIS Pro 2.2 software (ESRI, US) was used to estimate population count, counts of 3- and 4-way intersections, and business destinations within a 400m radius (circular buffer) of geocoded 6-digit residential postal codes of participants. Due to confidentiality, complete household street address information was not available; however, geocoded urban postal codes provide valid estimates of household geographical location within the Canadian context (Bow et al., 2004). The geocoding of the 6-digit residential postal code was undertaken using the CanMap Postal Code Suite (Desktop Mapping Technologies Inc.; DMTI). A 400m buffer represents the approximate distance travelled after 5 minutes of walking (James et al., 2014; Mackenbach et al., 2019). Population count was calculated by the Statistics Canada 2006 census dissemination block-level data. Provincial street network file from the DMTI Spatial CanMap Route Logistics was used to assess the counts of 3- and 4-way intersections within the buffers. An enhanced point of interest file from DMTI Spatial CanMap Route Logistics was used as a data source for estimating business destinations. Seventy-six Standard Industrial Classification codes of business destinations were selected to estimate counts of destinations within the buffer. These Standard Industrial Classification codes represented Retail Trade, Finance, Insurance, Real Estate, Services, and Public Administration (e.g., grocery stores, restaurants, banks, libraries, liquor stores, museums, schools, and universities). Destinations identified from SIC codes have acceptable agreement within the Canadian context compared with field observations (Paquet et al., 2008). These built environment features are relatively semi-permanent and temporally stable in the Canadian context (Creatore et al., 2016).

Space syntax walkability was measured using the following formula (Koohsari et al., 2016a): Space syntax walkability = z[z(population density) + 2 × z(street integration)]

Space syntax measure of street integration was calculated for each street segment using Axwomen (Jiang, 2012) and DepthMap (Turner, 2004) software considering all the other street segments within 1.6 km distance from its centre. Space syntax measures are based on the concept of “axial lines”, which correspond to lines of sight (Liu and Jiang, 2012). Space syntax measure of street integration represents how syntactically close a street segment is to other streets in the network (Klarqvist, 2015). Fewer changes in directions are needed to reach a highly integrated street segment, whereas less integrated street segments (typically like cul-de-sacs) require more turns to arrive at one’s destination (Kostakos, 2010). Figure 7 shows (a) a neighbourhood block schematic, (b) its axial lines, and (c) the levels of integration for streets.

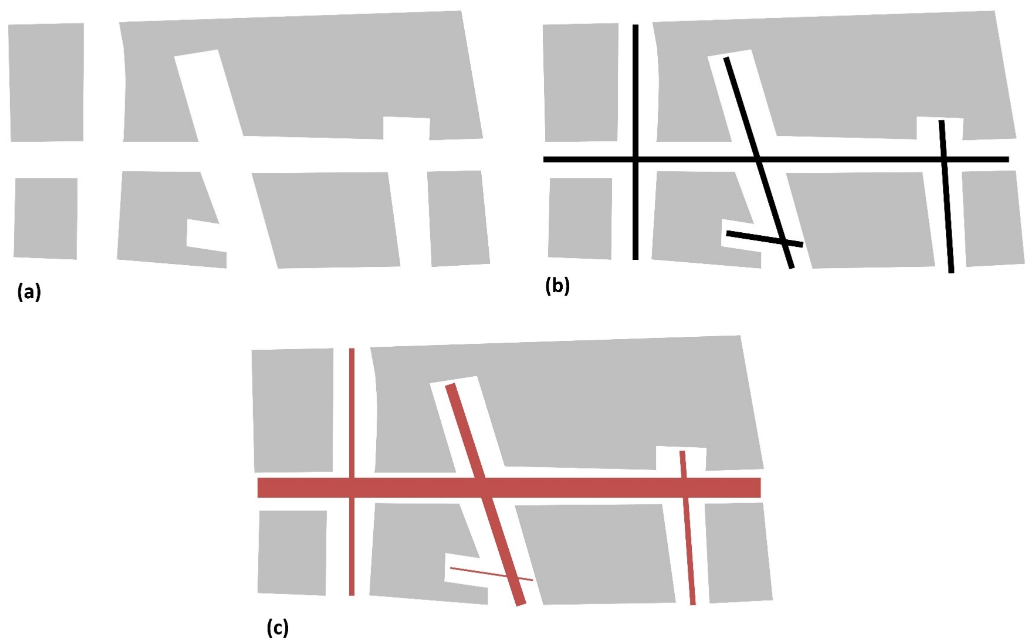


Figure 8. (a) a neighbourhood block, (b) its axial lines, and (c) the levels of integration for streets (ticker lines show higher integration level)

Statistical Analysis

Covariates and built environment indices were analysed using descriptive statistics. Independent t-tests and Pearson's chi-square test were used to compare these variables between women and men. Pearson's correlation coefficient between traditional walkability and space syntax walkability was calculated. Multivariate Tobit regression models were used to estimate the associations between each built environment metric and each cardio-metabolic outcome (LDL-cholesterol, HDL-cholesterol, triglycerides, systolic and diastolic blood pressure, HbA1c, and BMI) adjusting for covariates (b = unstandardised regression coefficients and 95% CI). Multivariate logistic regressions were used to estimate the odds ratios (ORs) and 95% confidence intervals (CIs) for the associations between each built environment metric and each binary cardio-metabolic outcome adjusting for covariates. Furthermore, each built environment metric was examined separately in each model. A complete-case analysis was chosen because the percentage of missing data for our variables of interest was low (<4%) (Jakobsen et al., 2017). Analyses were conducted using Stata 15.0 (Stata Corp., College Station, TX, US), and the level of significance was set at $p < 0.05$.

5.4.3. Results

Table 10 shows the characteristics of study participants. Approximately 67% of the sample were women (n=4,805), 75% were married or had live-in partners, 18% had some or entire high school training, 90% were Caucasian, 68% were employed (full-time or part-time), 94% were non-smokers, and 48% reported an annual household income of >$100,000. In this sample, 24% had elevated LDL-cholesterol, 15% had low HDL-cholesterol levels, 43% had elevated triglycerides, 14% had elevated blood pressure, 7% had elevated HbA1c, and 65% were overweight/obese. There were significant differences ($p < 0.05$) in several sociodemographic characteristics, including age, marital status, highest education level, and annual household income between women and men. No significant differences ($p < 0.05$) were found in the neighbourhood built environment metrics between women and men (Table 11). There were significant differences in the participants' clinically-assessed cardio-metabolic risk factors between women and men. The correlation between the traditional walkability and space syntax walkability was 0.77 ($p < 0.01$).

Table 10. Characteristics of study participants

Variable	Total (n=7,171)	Women (n=4,805)	Men (n=2,366)	p^a
	Mean (SD) or N (%)	**Mean (SD) or N (%)**	**Mean (SD) or N (%)**	
Age (years)	54.09 (9.45)	53.3 (9.3)	55.7 (9.5)	0.00
Marital status				
Married or not married, but living with someone	5385 (75.1)	3404 (70.8)	1981 (83.7)	0.00
Separated or divorced	995 (13.9)	812 (16.9)	183 (7.7)	
Widowed	285 (4.0)	233 (4.8)	52 (2.2)	
Single, never married	506 (7.1)	356 (7.4)	150 (6.3)	
Highest education level				
Some or entire high school	1305 (18.2)	917 (19.1)	388 (16.4)	0.00
Some or entire technical college training	2591 (36.1)	1755 (36.5)	836 (35.3)	
Some or entire university degree	2288 (31.9)	1549 (32.2)	739 (31.2)	
Some or entire university postgraduate degree	987 (13.8)	584 (12.2)	403 (17.0)	
Ethnicity				

Caucasian	6463 (90.1)	4333 (90.2)	2130 (90.0)	0.83
Other ethnicities	708 (9.9)	472 (9.8)	236 (10.0)	
Employment status				
Employed (full-time or part-time)	4905 (68.4)	3259 (67.8)	1646 (69.6)	0.14
Unemployed	2266 (31.6)	1546 (32.2)	720 (30.4)	
Current smoking status				
Non-smokers (includes former smokers)	6725 (93.8)	4521 (94.1)	2204 (93.2)	0.13
Smokers	446 (6.2)	284 (5.9)	162 (6.8)	
Annual household income (Canadian Dollars)				
$0 to 49,999	1058 (14.8)	782 (16.3)	276 (11.7)	0.00
$50,000 to 74,999	1081 (15.1)	752 (15.7)	329 (13.9)	
$75,000 to 99,999	1077 (15.0)	713 (14.8)	364 (15.4)	
$100,000 to 149,999	1560 (21.8)	976 (20.3)	584 (24.7)	
$150,000 to 199,999	921 (12.8)	594 (12.4)	327 (13.8)	
$200,000 or more	969 (13.5)	611 (12.7)	358 (15.1)	
Refused to answer	505 (7.0)	377 (7.8)	128 (5.4)	

[a] Based on independent *t* test or $\chi 2$ test.

Table 11. Participants' neighbourhood built environment metrics

	Total (n=7,171)	Women (n=4,805)	Men (n=2,366)	p^a
	Mean (SD)	**Mean (SD)**	**Mean (SD)**	
Traditional walkability	0.00 (2.63)	-0.00 (2.64)	0.0 (2.62)	0.95
Space syntax walkability	0.0 (1.00)	-0.01 (1.01)	0.02 (0.99)	0.30

[a] Based on independent *t* test.

Table 12 shows the associations of neighbourhood built environment metrics with cardio-metabolic risk factors among women and men. After adjusting for covariates, space syntax walkability was negatively associated with systolic and diastolic blood pressure among men (b=-0.87, 95% CI -1.43, -0.31, p = 0.002 and b=-0.45, 95% CI -0.86, -0.04, p = 0.030, respectively). No significant associations were observed among women.

Table 13 presents the logistic regression analysis for the associations of neighbourhood built environment metrics with the binary cardio-metabolic risk factors among women and men. Space syntax walkability was associated with lower odds of overweight/obese among women and men (OR=0.93, 95% CI 0.87, 0.99, p = 0.010 and OR=0.88, 95% CI 0.79, 0.97, p = 0.015, respectively). There were no significant associations between any built environment metrics and elevated LDL-cholesterol, low HDL-cholesterol, elevated triglycerides, elevated blood pressure, and elevated HbA1c for women or men.

Table 12. Associations of neighbourhood built environment metrics with clinically assessed cardio-metabolic risk factors

	Low-density lipoprotein (LDL)-cholesterol	High-density lipoprotein (HDL)-cholesterol	Triglycerides	Systolic blood pressure	Diastolic blood pressure	Hemoglobin A1c	Body mass index
	***b* (95% CI)**	***b* (95% CI)**	***b* (95% CI)**	***b* (95% CI)**	***b* (95% CI)**	***b* (95% CI)**	***b* (95% CI)**
Among women							
Traditional walkability	-0.01 (-0.02, 0.00)	0.00 (-0.00, 0.01)	0.00 (-0.01, 0.01)	-0.03 (-0.19, 0.12)	-0.02 (-0.13, 0.09)	0.00 (-0.01, 0.01)	-0.03 (-0.09, 0.04)
Space syntax walkability	-0.02 (-0.05, 0.01)	0.01 (-0.01, 0.02)	0.00 (-0.03, 0.03)	-0.33 (-0.73, 0.07)	-0.14 (-0.43, 0.14)	0.01 (-0.02, 0.03)	-0.11 (-0.28, 0.06)
Among men							
Traditional walkability	-0.00 (-0.02, 0.01)	0.00 (-0.00, 0.01)	-0.01 (-0.03, 0.01)	-0.19 (-0.40, 0.03)	-0.06 (-0.21, 0.10)	-0.00 (-0.02, 0.01)	-0.02 (-0.09, 0.05)
Space syntax walkability	-0.01 (-0.05, 0.04)	0.01 (-0.01, 0.02)	-0.02 (-0.07, 0.03)	-0.87 (-1.43, -0.31)[a]	-0.45 (-0.86, -0.04)[b]	-0.04 (-0.08, 0.01)	-0.13 (-0.32, 0.05)

Note *b*= unstandardised regression coefficients; CI= confidence interval; population count, 3-way intersections, 4-way intersections, business destinations, space syntax connectivity, and space syntax street integration were standardised (i.e., z-scores) prior to the regression analysis; All models adjusted for age, marital status, highest education level, ethnicity, employment status, current smoking status, and annual household income; Each built environment attribute was examined separately in each model.

[a] $p < 0.02$.

[b] $p < 0.05$.

Table 13. Binary logistic regression analysis for the associations of neighbourhood built environment metrics with clinically assessed cardio-metabolic risk factors

	Elevated LDL-cholesterol[a]	Low HDL-cholesterol[b]	Elevated triglycerides[c]	Elevated blood pressure[d]	Elevated HbA1c[e]	Overweight/Obese[f]
	OR (95% CI)	**OR (95% CI)**	**OR (95% CI)**	**OR (95% CI)**	**OR (95% CI)**	**OR (95% CI)**
Among women						
Traditional walkability	0.98 (0.95, 1.00)	0.96 (0.92, 1.00)	1.00 (0.98, 1.02)	1.02 (0.98, 1.05)	1.00 (0.95, 1.05)	0.98 (0.96, 1.00)
Space syntax walkability	0.96 (0.90, 1.03)	0.89 (0.80, 1.00)	1.00 (0.94, 1.07)	0.98 (0.89, 1.08)	1.02 (0.89, 1.15)	0.93 (0.87, 0.99)[g]
Among men						
Traditional walkability	1.01 (0.97, 1.05)	1.01 (0.97, 1.04)	1.00 (0.97, 1.03)	0.98 (0.94, 1.02)	1.03 (0.89, 1.19)	0.98 (0.94, 1.02)
Space syntax walkability	1.01 (0.91, 1.12)	1.04 (0.95, 1.14)	0.97 (0.89, 1.05)	0.90 (0.81, 1.01)	1.00 (0.95, 1.06)	0.88 (0.79, 0.97)[g]

Note OR= odds ratio; CI= confidence interval; population count, 3-way intersections, 4-way intersections, business destinations, space syntax connectivity, and space syntax street integration were standardised (i.e., z-scores) prior to the regression analysis; All models adjusted for age, marital status, highest education level, ethnicity, employment status, current smoking status, and annual household income; Each built environment attribute was examined separately in each model; The level of significance was set at $p < 0.05$.

[a] Elevated LDL-cholesterol concentration defined as above borderline high concentration (≥ 3.37 mmol/L) versus optimal/near optimal (<3.37 mmol/L; reference group).

[b] Low HDL-cholesterol concentration defined as <1.04 mmol/L versus normal (≥1.04 mmol/L; reference group).
[c] Elevated triglyceride concentration defined as ≥ 1.70 mmol/L versus normal (<1.7 mmol/L; reference group).
[d] Elevated blood pressure defined as systolic ≥140 or diastolic ≥90 versus normal (systolic <140 or diastolic <90; reference group).
[e] Elevated Hemoglobin A1c concentration (HbA1c) defined as ≥6.5% versus normal (<6.5%; reference group).
[f] Overweight/obese defined as body mass index ≥25 kg/m^2 versus normal (<25 kg/m^2; reference group).
[g] $p < 0.02$.

5.4.4. Discussion

This is one of the few studies investigating the extent to which the neighbourhood built environment is associated with cardio-metabolic clinical risk factors. Notably, no studies have linked the novel space syntax built environment metrics with cardio-metabolic clinical risk factors to the best of our knowledge. Our findings showed that the space syntax walkability was associated with lower odds of overweight/obese in women. Additionally, the novel composite index of space syntax walkability was negatively associated with systolic and diastolic blood pressure and the odds of overweight/obese among men.

Several previous studies explored the associations between built environment characteristics, lipid profile, blood pressure, and HbA1c (Braun et al., 2016a; Braun et al., 2016b; Loo et al., 2017; Méline et al., 2017). For instance, in a cross-sectional study undertaken in Canada, compared with the lowest quartile of walkability (measured by Walk Score®), for all age groups combined, residents from neighbourhoods in the highest quartile of walkability had significantly lower systolic and diastolic blood pressure, higher HDL-cholesterol, and lower HbA1c (Loo et al., 2017). A cross-sectional study conducted in France found that higher Walk Score® was negatively associated with systolic and diastolic blood pressure (Méline et al., 2017). In the US, a study found that higher Walk Score® was cross-sectionally associated with lower blood pressure; however, an increase in Walk Score® was associated with increases in triglycerides and blood pressure over time (Braun et al., 2016a). While findings from these studies provide some support for our overall finding that specific neighbourhood built environment characteristics are associated with cardio-metabolic risk factors, they differ in that we found no associations with LDL-cholesterol, HDL-cholesterol, triglycerides, or HbA1c. The exact reasons for these differences remain speculative. Changes in these risk factors may be less sensitive to minor differences in the neighbourhood built environment metrics or more influenced by the food environment. Further research is needed to shed light on this issue.

Our study adds to previous findings and extends them by testing how the novel built environment metrics based on the space syntax theory are associated with cardio-metabolic risk factors. There has been a call by urban design and public health experts to develop more policy-relevant evidence in the built environment and health field (Giles-Corti et al., 2015). Traditional walkability measures incorporate information from multiple data sources that are not always available, complete, or in the same format for all geographical locations (e.g., municipalities). These walkability indices, while informative, cannot be easily converted into a specific urban design policy (Koohsari et al., 2016a). Our findings also suggest that space syntax derived walkability may better predict cardio-metabolic risk factors compared with a traditional walkability index. As a well-established theory/method among built environment professions (Karimi, 2012), space syntax built environment metrics can be more easily converted into practice or policy than traditional walkability measures. Space syntax provides metrics of the built environment that have practical meaning for urban designers and can also identify optimal locations for destinations that support walking and other physical activity (Koohsari et al., 2019b). Furthermore, space syntax built environment metrics are less data-dependent and can be calculated using readily available network spatial data, which can enhance the replicability of the studies across geographical locations (Koohsari et al., 2016a).

Our results showed that the novel space syntax built environment metric was pronouncedly associated with BMI in women and men. There are mixed findings on the associations between the walkable built environment and weight status measures (Mackenbach et al., 2014; Paulo Dos Anjos Souza Barbosa et al., 2019; Yang et al., 2021). While several studies demonstrated a negative association between the traditional walkability indices and BMI or waist circumference (Hajna et al., 2018; Loo et al., 2017; McCormack et al., 2018; Müller-Riemenschneider et al., 2013), some other studies reported null findings (Braun et al., 2016a; Duncan et al., 2015). Traditional walkability indices, including neighbourhood walkability and Walk Score®, are usually calculated based on built environment values within certain buffer distances such as 800m, 1km, and 1.6 km around participants' residential location (Frank et al., 2010; Walk Score, 2020). Therefore, it is possible that traditional walkability indices may not truly detect the spatial areas within which people are physically active (Koohsari et al., 2018a). Note, however, that other conceptual and operational definitions of traditional walkability indices exist (Forsyth, 2015; Maghelal and Capp, 2011). Thus, we cannot make assumptions about the predictive validity of these other measures based on the findings related to the traditional walkability index tested in our study. In contrast, space syntax metrics conceptualise the built environment by considering how each space is integrated into the spaces' network. Therefore, space syntax measures inherently represent the larger areas affecting people's activities, impacting weight measures. Nevertheless, one previous study conducted in Australia did not find a significant association between space syntax walkability and weight change over four years (Koohsari et al., 2018a). However, they used self-reported weight measures, which may be subjected to recall bias. Further longitudinal research is needed to explore how novel space syntax built environment metrics may be associated with clinical weight measures over time.

This study has some limitations. Causal relationships cannot be inferred from our cross-sectional analysis, especially as there is no historical data on the levels of cardio-metabolic risk factors when individuals resided in their current neighbourhoods. The built environment metrics were calculated by defining spatial buffers around participants' residential locations. However, these spatial buffers may not necessarily match the actual built environment to which people are exposed (Holliday et al., 2017). Depending on their level of mobility, people are exposed to various built environment characteristics in their daily activities (Kwan, 2013), which each can differently affect people's cardio-metabolic risk factors. Our study focused on built characteristics within considered to be within a conveniently walkable distance from participants homes (e.g., the residential neighbourhood within 400m). Future studies using a combination of GIS and a global positioning system can precisely identify and conceptualise people's activity spaces (Perchoux et al., 2019). Furthermore, as our study relied on existing data, we were not able to include all hypothesised cardio-metabolic risk factors. When synthesising the evidence, the reported potential risk of the walkable built environment on some cardio-metabolic risk factors (e.g., C-reactive protein) must be considered (Braun et al., 2016b; King, 2013). Additionally, we observed variations in the associations when stratified by sex. Notably, several cardiovascular biomarkers may be sensitive to age disparities between sexes. Future studies should explore in detail on how stratification sample by age and sex groups may affect the findings. The study's strengths include the use of the novel neighbourhood built environment metrics and examining the clinically-assessed cardio-metabolic risk factors in relatively large samples of men and women.

5.3. Chapter summary and conclusions

This chapter consisted of four individual studies published as four peer-reviewed papers. As the first study in the context of Asia, the first study examined the associations between Walk Score® and active and sedentary behaviours in Japan. This study found for the first time that Walk Score® was related to physically-active and sedentary travel behaviours in a non-Western country. Walk Score® appears to be a useful tool for urban designers/planners and health advocates to identify local areas that support or hinder residents' active travel. Such knowledge, obtained easily through an online resource, will help develop environmental initiatives to promote active living and better health outcomes.

The second study found that several space syntax measures were also related to active and sedentary outcomes in Japan. Although there have been a growing number of studies examining if and how built environment attributes are related to active and sedentary behaviours in Western countries, there is limited research on this topic in non-Western countries. Our study shows that previous findings from Western countries, i.e., the association of street connectivity with travel behaviours, are also applicable to Japan. Further research in Asian countries, where physical inactivity is becoming a serious health concern, is needed to inform urban design initiatives to promote active living.

The third study, as the first study on this topic, tested the associations between space syntax walkability index and sedentary behaviour. This study suggests that urban design attributes may have an influence on adults' sedentary behaviours. Notably, our findings highlight that the composite measure of SSW, which can be calculated using readily-available geographical data, is associated with leisure screen time and car driving. Neighbourhoods with well-connected street layouts and higher residential density were supportive of reducing two common adults' sedentary behaviours in a Canadian environment. Such evidence can help urban designers and policymakers in developing environmental guidelines to (re)design neighbourhoods in order to support adults' healthy behaviours in the Canadian context. Application of SSW can extend research on built environment correlates on sedentary behaviours into different geographical locations, where obtaining geographically detailed data is a challenge.

The final study tested the associations between space syntax walking, traditional walkability and clinically-assessed cardiometabolic risk factors. Although an association was observed between space syntax walkability and these biomarkers, no association was found for traditional walkability. This study showed that the novel built environment metric based on the space syntax theory was associated with some cardio-metabolic risk factors including blood pressure and weight status. One implication of these findings is that it might be possible to identify neighbourhoods with poorly built environments and then target these environments for interventions specific to improving/preventing the cardio-metabolic risk factors. Further studies are needed to extend these findings in different geographical contexts and elucidate the pathways between neighbourhood built environment and cardio-metabolic risk factors.

The following chapter will provide an overview of the overall thesis and highlight t the future directions on this area of research.

Chapter 6. Conclusions and future directions

6.1. The contribution of this PhD research to health and sport sciences

This PhD research has made significant contributions to health and sport sciences through addressing several gaps in the current literature on built environment and cardiovascular disease. This PhD research specifically and deceivably advanced the field by exploring, validating, testing, and discussing two built environment tools, Walk Score® and space syntax to address three methodological and policy-relevant gaps in this area of research (Figure 8). One of the notable strengths of this PhD research lies in its inclusion of case studies conducted not only in highly populated areas of Japan but also in sprawled low-density areas in Canada. This multi-site approach enhances the variability in built environment attributes.

Emerging research from Asian and Western counties demonstrates the potential impact of urban design on cardiovascular disease. While motivating individual lifestyle changes (e.g., targeting individuals through behaviour change strategies) remains essential in preventing these diseases, sustainable built environment interventions that can impact a high percentage of the population are needed. Nevertheless, the science of modifying the built environment to enhance cardiovascular health outcomes is still in its infancy, with several challenges. This PhD thesis identified the key conceptual, methodological, and policy-relevant issues on the activity-friendly built environment and cardiovascular disease. Notably, this PhD thesis discussed how two built environment tools, Walk Score® and space syntax, can address some of this topic's methodological and policy-relevant issues. This chapter was published in one peer-reviewed journal (Koohsari and Oka, 2023).

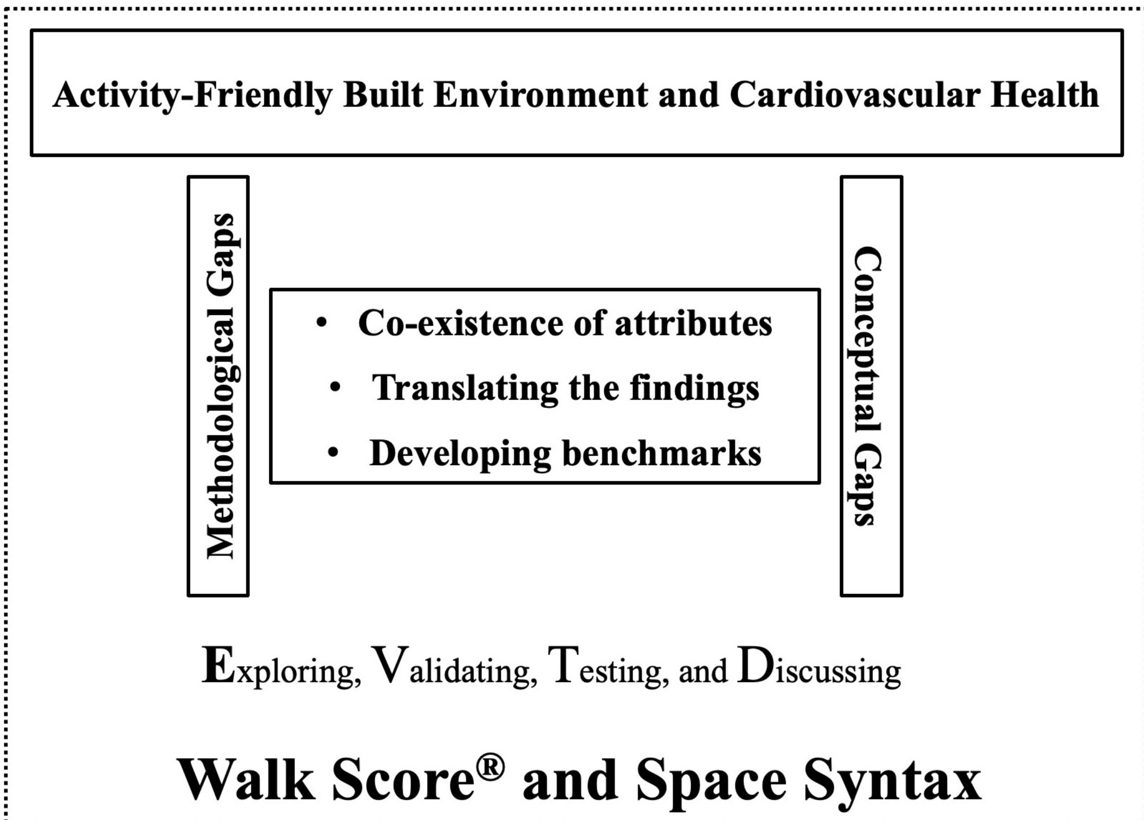


Figure 9. The contribution of this PhD research to health & sport sciences

6.2. Future recommendations for the activity-friendly built environment and cardiovascular disease

One of the critical challenges in the research on the built environment, active living, and cardiovascular health is that built environment characteristics co-exist in the real world and act together with people's behaviour (Koohsari et al., 2020a). It is then essential to investigate how composite built environment indices may influence active and sedentary behaviours. Neighbourhood walkability is a built environment index frequently used to understand built environment and physical activity relationships (Frank et al., 2010). It consists of four variables: population density, land use mix, intersection density, and net retail area ratio. Neighbourhood walkability has been found to be associated with active and sedentary behaviour across different countries (Frank et al., 2010; Kaczynski and Glover, 2012; Koohsari et al., 2014b; Owen et al., 2007b). However, this index requires detailed parcel-level spatial data, which are commonly unavailable or difficult to access (Kerr et al., 2013; Salvo et al., 2014). Additionally, this index is usually calculated by GIS. Managing and analysing data using GIS software requires extensive training and unique computer equipment, which is an additional limitation. This special equipment and expertise may not be available to many local policymakers and developers to calculate this index. These issues underscore the need for developing and testing easily-available environmental indices in relation to active and sedentary behaviour is necessary.

Walk Score® is a publicly-available tool that allocates a score to any given geographical address (www.walkscore.com). Walk Score® employs a decay function to give a raw score to each address based on its network distance to near destinations such as stores, cafes, grocery stores, banks, restaurants, schools, bookshops, parks, fitness centres, and restaurants within a mile (1.6km) from that address (Walk Score, 2020). It then standardises the score from 0 to 100 with an adjustment of population density and road metrics (intersection density and block length) around that address. Higher scores correspond to locations with more destinations nearby and conducive to walking. As discussed in previous chapters, Walk Score® has the potential to provide the field with a practical, easy-to-use tool to identify areas supportive of active behaviours.

Another critical challenge in (re)designing the built environment to encourage active living and cardiovascular health is developing policy-relevant benchmarks (Koohsari et al., 2020a). Many studies have reported the significant 'associations' between built environment characteristics and physical activity. However, it remains challenging how to translate these findings into urban design and public health policies. There has been a recent urgent call to develop and test innovative built environment measures and indices that can provide policy-relevant knowledge on the built environment and cardiovascular health (Nichani et al., 2021). Space syntax can be one of the innovative methods to conceptualise the built environment supporting cardiovascular health.

Space syntax is a concept and method that has been established primarily in the fields of urban design and architecture. It was introduced mainly by Hillier & Hanson (1984) in their seminal book, The social logic of space. They proposed a spatial configuration approach to understand space and social life interactions. Space syntax is defined as "a research program that investigates the relationship between human societies and space from the perspective of a general theory of the structure of inhabited space in all its diverse forms: buildings, settlements, cities, or even landscapes" (Bafna, 2003). Space syntax can analyse the effect of the configuration of built environments on residents' movement. Although pedestrian movement was the original core of space syntax theory (Ratti, 2004), it has been widely employed to solve social problems such as crime, housing prices, and environmental cognition. As shown in previous chapters, space syntax theory and method could address several of the limitations of the previous studies on activity-friendly built environment and cardiovascular disease. Notably, modifying the built environment is challenging and, in certain instances, may be impossible. However, these tools can provide valuable resources for targeting the most modifiable elements of the built environment, such as land uses, to effectively influence health behaviours.

Modifying the built environment attributes is likely to be effective in triggering behaviours conducive to cardiovascular health. In contrast with most individually-based strategies, built environmental changes to promote active and sedentary behaviours can affect a large number of the population lasting for a long time (Marteau et al., 2012). Although this new, interdisciplinary field of science is promising, understanding the challenges in the relationships between the built environment and cardiovascular disease must be improved.

6.3. Future directions for investigations

As discussed above, the application of Walk Score® and space syntax can address several challenges on this topic. The following issues, however, need to be considered to move research in this field forwards (Koohsari and Oka, 2023):

- Explore how Walk Score® and space syntax measures may influence active and sedentary behaviours across different geographical contexts.
- Test the concurrent validity of Walk Score® and objectively assessed walkability measures in different countries.
- Develop standard manuals to consistently conceptualise and measure the built environment using space syntax with active and sedentary behaviours.
- Explore the validity of Walk Score® as a measure of activity-friendly built environments across different regions and countries.
- Conduct longitudinal studies (i.e., movers versus non-movers) using Walk Score® and space syntax measures.
- Identify Walk Score® thresholds necessary to influence the behaviours promoting cardiovascular health.

- Examine how space syntax measures are related to objectively assessed physical activity and sedentary behaviours.

- Explore how new technologies such as geospatial artificial intelligence can be combined with space syntax to analyse built environments supporting cardiovascular health.

- Examine the effects of walkable and food environments simultaneously in relation to cardiovascular outcomes.

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