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The contributions of neighbourhood design in promoting metabolic health

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The design and quality of the neighbourhood built environment can encourage health-supportive behaviours and support cardiometabolic health. However, despite the relationships between demographic and behavioural risk factors of metabolic syndrome being investigated by many studies, only some studies have directly estimated the associations between the built environment and metabolic syndrome. Using data from Canada, we examined the associations between the neighbourhood built environment and metabolic syndrome. Data from Alberta's Tomorrow Project participants, conducted in Alberta, Canada, was used ($n = 6718$). Metabolic syndrome was defined as the presence of at least three clinical risk factors among lipid levels, blood pressure, and waist circumference. The normalised difference vegetation index was used to quantify the greenness of each participant's neighbourhood. Built attributes of participants' neighbourhoods associated with supporting physical activity, including dwelling density, intersection density, and the number of points of interest, were obtained via the Canadian Urban Environmental Health Research Consortium. Increases in the number of points of interest and total active living environment-friendliness of the neighbourhood were associated with having fewer metabolic syndrome risk factors ($b = -0.11$, 95% CI −0.16, −0.07 and $b = -0.03$, 95% CI −0.05, −0.01, respectively) and lower odds of metabolic syndrome (OR = 0.89, 95% CI 0.84, 0.094 and OR = 0.97, 95% CI 0.95, 0.99, respectively). Furthermore, higher dwelling density was associated with having fewer metabolic syndrome risk factors ($b = -0.05$, 95% CI −0.09, −0.01). Our findings highlight the importance of urban design to prevent and potentially manage metabolic syndrome and improve population health.

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Introduction

Globally, cardiovascular diseases such as heart disease or stroke are the leading cause of mortality, representing 32% of all deaths: 17.9 million died due to these diseases in 2019 (World Health Organization, 2021). Despite a slight decrease in the incidence of cardiovascular diseases in the past decade (Amini et al., 2021), modifiable clinical risk factors that compromise cardiovascular health (e.g., hypertension, hyperlipidemia, excess weight, and hyperglycaemia) remain prevalent in populations (Roth et al., 2020). For instance, in the United States, approximately half of adults (108 million) have hypertension, defined as blood pressure ≥130/80 mm Hg (Centers for Disease Control and Prevention, 2018). In Canada, 26.4% of adults were obese, with a body mass index of ≥30 kg/m^2 in 2016 (Twells et al., 2020). According to the Canadian Chronic Disease Surveillance System, in 2017, the age-standardised population prevalence was approximately 8.1% for diabetes mellitus (excluding gestational) and 23.5% for hypertension (excluding gestational) (Public Health Agency of Canada, 2018). Identifying sustainable interventions that can positively affect clinical risk factors among large population segments is needed to reduce cardiovascular diseases.

Metabolic syndrome is defined as a cluster of clinical and anthropometric risk factors, such as hypertension and obesity, which significantly increases the likelihood of cardiovascular diseases (Bonora, 2006; Grundy, 2016) and cardiovascular-related and all-cause mortality (Lakka et al., 2002). Metabolic syndrome could be the route to many chronic diseases (such as diabetes and cardiovascular diseases); they are the clinical markers that elevate before the established disease takes hold. Studies across different countries consistently indicate a high prevalence of metabolic syndrome in adults (Cameron et al., 2007; Hirode and Wong, 2020; Li et al., 2016; Shojaeimotlagh et al., 2019). For example, in the United States, the prevalence of metabolic syndrome among adults aged 20 years and older was found to be 34.7% (Hirode and Wong, 2020). A systematic review and meta-analysis of studies in China found that 24.5% of their pooled sample of adults aged ≥15 had metabolic syndrome (Li et al., 2016). Gender differences in the prevalence of metabolic syndrome have been consistently observed in several studies, indicating that men are more likely than women to have metabolic syndrome (Regitz-Zagrosek et al., 2007; Regitz-Zagrosek et al., 2006). Several behavioural interventions have been identified for preventing and managing metabolic syndrome (Han and Lean, 2015; Wang et al., 2020). Notably, mounting evidence highlights the importance of accumulating physical activity for managing and preventing metabolic syndrome (Lakka and Laaksonen, 2007; Ostman et al., 2017; Zhang et al., 2017).

The aim of this study was to estimate the associations between an activity-friendly built environment and metabolic syndrome in a sample of Canadian adults. Specifically, we estimate the associations between physical activity-supportive neighbourhood built characteristics and: (1) being classified as having metabolic syndrome and (2) the frequency of metabolic syndrome clinical risk factors.

Literature review

There is the potential to (re)design neighbourhoods with built environment characteristics that promote health and prevent non-communicable diseases. According to the principles of nudge theory and behavioural insights (Hallsworth and Kirkman, 2020; Thaler and Sunstein, 2009), the built environment promotes health-supportive behaviours (e.g., physical activity) by providing individuals with healthy choices without mandating them (Sallis et al., 2012). Previous evidence provided behavioural insights that modifications to the built environment also have the potential to reach large segments of the population and last for a long term (Gostin, 2014). For instance, allocating a new well-designed park in a neighbourhood has the potential to influence residents' activities over the years.

Several conceptual frameworks posit how built environment characteristics can influence population health (Frank et al., 2019; Northridge et al., 2003). Frank et al. (2019) provided a framework linking transportation systems, land use, pedestrian environment, and green space to the chronic diseases of city dwellers. Built environment characteristics such as buildings, destinations, sidewalks, and green spaces are associated with physical activity, diet, pollution, social interactions, and sedentary behaviour (Koohsari et al., 2020; Zhang et al., 2022). Notably, physical activity is a crucial behaviour linking the built environment with health and chronic diseases (Kärmeniemi et al., 2018; Tcymbal et al., 2020). For example, a systematic review and meta-analysis of prospective studies found that improved access to destinations and active transportation infrastructure supported transportation walking (Kärmeniemi et al., 2018). Another systematic review of longitudinal studies found that building new walking/cycling infrastructure and improving public transportation was associated with higher physical activity (Tcymbal et al., 2020).

Based on this evidence, it is plausible that built environment characteristics that support physical activity can also reduce the risk of metabolic syndrome. Indeed, this is supported by findings from a systematic review, including 18 studies demonstrating that objectively measured and perceived built environment characteristics were associated with cardiovascular disease risk factors (Malambo et al., 2016). Notably, only three studies included in this review focussed on metabolic syndrome, of which none were undertaken with Canadian populations (Malambo et al., 2016). Similarly, a recent scoping review of Canadian studies investigating the associations between the built environment and health outcomes found that few studies examined metabolic syndrome (McCormack et al., 2019).

However, there are inconclusive findings regarding the associations between physical activity-supportive built environments and metabolic syndrome. Although the relationships between built environment characteristics and behavioural risk factors of metabolic syndrome have been investigated by many studies (de Courrèges et al., 2021; McCormack and Shiell, 2011; Tcymbal et al., 2020), few studies have yet directly estimated the associations between neighbourhood built environment characteristics and metabolic syndrome (Braun et al., 2016; Coffee et al., 2013; de Keijzer et al., 2019; Leal and Chaix, 2011; Malambo et al., 2016; Yang et al., 2020). For example, a study in Australia examined the associations between an objective index of neighbourhood walkability and metabolic syndrome (Coffee et al., 2013). Another study conducted in the UK assessed the associations between residential greenness measured by the normalised difference vegetation index (NDVI) and vegetation continuous fields (VCF) with the risk of metabolic syndrome (de Keijzer et al., 2019). A study in China explored the associations between greenness and the prevalence of metabolic syndrome in adults (Yang et al., 2020). Further studies conducted in diverse contexts are necessary to provide a deeper understanding of this topic.

Methods

Data source and participants. Cross-sectional data from an existing province-wide cohort dataset from Alberta's Tomorrow Project (ATP) conducted in Alberta, Canada, was used in this study (The website of ATP: https://myatp.ca). Detailed study design and recruitment methods (for two phases of recruitment) have been documented elsewhere (Robson et al., 2016; Ye et al.,

2017). The ATP is a prospective cohort study across a Canadian province (Alberta) with a scheduled follow-up for at least 50 years (Ye et al., 2017). Briefly, the ATP recruitment had two stages: in the first stage, from 2000 to 2008, a random sample (via random digit dialling across the province) of adults (35 to 69 years) with no personal history of cancer (other than non-melanoma skin cancer) and with no intention of leaving Alberta in the following year was invited to enrol in ATP ($n = 63,486$). Questionnaires used to collect participant information were written in English. A total of 31,072 participants provided informed consent and completed a health and lifestyle survey. Reminder postcards were sent to nonrespondents 6 and 16 weeks after the initial mailing. ATP participants enrolled in the study were located in urban and rural areas within the province. A map showing the geographical distribution of participants' household locations within the province has been presented elsewhere (Robson et al. (2016)). Participants enrolled between 2000 and 2007 were invited to complete a follow-up health and lifestyle survey in 2008 ($n = 20,707$). In the second stage of ATP, from 2009 to 2015, ATP invited participants to attend study centres to collect physical measures (e.g., height, weight, body circumferences, and blood pressure) and biological samples (i.e., blood and urine). In this study, we present the findings of a cross-sectional analysis of data from participants enrolled in ATP who completed the 2008 health and lifestyle follow-up survey, underwent physical measurements, provided biological samples, and resided in urban areas. Postal code was used to link participant ATP data with the objective built environment data. Figure 1 describes the detailed workflow for the present analysis. This analysis was approved by the University of Calgary Conjoint Health Research Ethics Board (REB19-1992).

After excluding individuals with missing variables, a total of 6718 participants (4455 women, 2263 men) were included in this study. The characteristics of the study participants are summarised in Table 1. The participants had an average age of 54 years (with a minimum of 35 years, a maximum of 71 years, and an SD of 9.4 years), and the majority were women (66%), married or had live-in partners (75%), had some or entire technical college training (36%), were Caucasian (91%), were employed (full-time or part-time) (68%), were non-smokers (94%), and reported an annual household income of ≥$100,000 (48%). Approximately 51% of our sample had abdominal obesity (waist circumference; men: ≥102 cm and women: ≥88 cm), 43% had elevated triglycerides (≥1.7 mmol/L), 26% had reduced high-density lipoprotein (HDL)-cholesterol (men: <1.03 mmol/L and women: <1.30 mmol/L), 43% had elevated haemoglobin A1c (HbA1c ≥ 5.7%), and 32% had elevated blood pressure (systolic ≥130 or diastolic ≥85 mm Hg). The average number of metabolic syndrome risk factors was 1.95 (SD = 1.4), and 34% of participants had metabolic syndrome (≥3 risk factors). Abdominal obesity was the most common risk factor among participants with metabolic syndrome (87%). There were statistically significant differences ($p < 0.05$) observed in various sociodemographic characteristics, including age, marital status, highest education level, current smoking status, and annual household income between women and men. Additionally, these differences extended to metabolic syndrome risk factors.

Measures

Metabolic syndrome. Metabolic syndrome was defined based on the Adult Treatment Panel III definition, requiring the presence of at least three of the following components (National Cholesterol Education Program, 2002; Riediger and Clara, 2011): abdominal obesity (waist circumference ≥102 cm for men and ≥88 cm for women); elevated plasma triglyceride level (≥1.7 mmol/L); decreased high-density lipoprotein (HDL) cholesterol level (<1.03 mmol/L for men and <1.30 mmol/L for women); elevated blood pressure (systolic ≥130 or diastolic ≥85 mm Hg); or elevated fasting glucose level (≥6.1 mmol/L). Since fasting glucose was not collected, haemoglobin

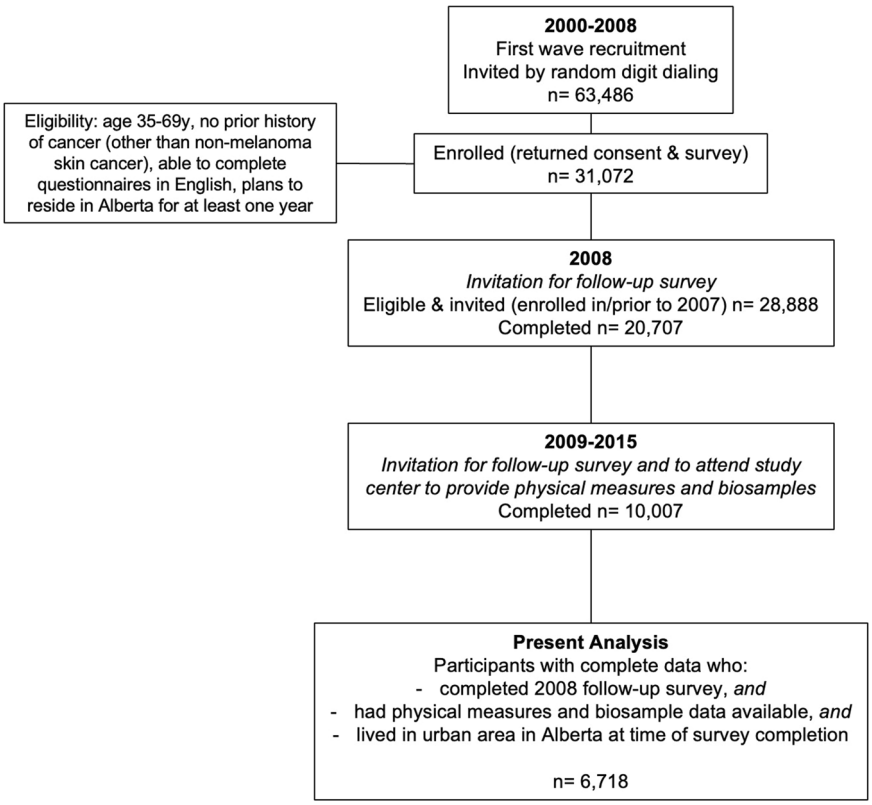

Fig. 1 Participants' recruitment process.

Table 1 Characteristics of study participants.

Variable	Total ($n = 6718$) Mean (SD) or N (%)	Women ($n = 4455$) Mean (SD) or N (%)	Men ($n = 2263$) Mean (SD) or N (%)	p^a
Age (years)	54.3 (9.4)	53.5 (9.3)	55.9 (9.4)	0.000
Marital status				
Married or not married, but living with someone	5041 (75.0)	3152 (70.8)	1889 (83.5)	0.000
Separated or divorced	926 (13.8)	747 (16.8)	179 (7.9)	
Widowed	271 (4.0)	219 (4.9)	52 (2.3)	
Single, never married	480 (7.1)	337 (7.6)	143 (6.3)	
Highest education level				
Some or entire high school	1211 (18.0)	840 (18.9)	371 (16.4)	0.000
Some or entire technical college training	2433 (36.2)	1621 (36.4)	812 (35.9)	
Some or entire university degree	2146 (31.9)	1449 (32.5)	697 (30.8)	
Some or entire university postgraduate degree	928 (13.8)	545 (12.2)	383 (16.9)	
Ethnicity				
Caucasian	6084 (90.6)	4031 (90.5)	2053 (90.7)	0.791
Other	634 (9.4)	424 (9.5)	210 (9.3)	
Employment status				
Employed (full-time or part-time)	4567 (68.0)	3011 (67.6)	1556 (68.8)	0.333
Unemployed	2151 (32.0)	1444 (32.4)	707 (31.2)	
Current smoking status				
Non-smokers (including former smokers)	6300 (93.8)	4196 (94.2)	2104 (93.0)	0.030
Smokers	418 (6.2)	259 (5.8)	159 (7.0)	
Annual household income (Canadian Dollars)				
$0 to 49,999	997 (14.8)	726 (16.3)	271 (12.0)	0.000
$50,000 to 74,999	1026 (15.3)	704 (15.8)	322 (14.2)	
$75,000 to 99,999	1019 (15.2)	670 (15.0)	349 (15.4)	
$100,000 to 149,999	1458 (21.7)	898 (20.2)	560 (24.7)	
$150,000 to 199,999	839 (12.5)	540 (12.1)	299 (13.2)	
$200,000 or more	893 (13.3)	558 (12.5)	335 (14.8)	
Refused to answer	486 (7.2)	359 (8.1)	127 (5.6)	
Abdominal obesity (waist circumference ≥102 cm for men and ≥88 cm for women	3412 (50.8)	2433 (54.6)	979 (43.3)	0.000
Elevated triglycerides (≥1.7 mmol/L)	2913 (43.4)	1665 (37.4)	1248 (55.1)	0.000
Reduced High-density lipoprotein (HDL)-cholesterol (<1.03 mmol/L for men and <1.30 mmol/L for women)	1721 (25.6)	1071 (24.0)	650 (28.7)	0.000
Elevated haemoglobin A1c (≥5.7%)	2895 (43.1)	1812 (40.7)	1083 (47.9)	0.000
Elevated blood pressure (systolic ≥130 or diastolic ≥85 mm Hg)	2150 (32.0)	1140 (25.6)	1010 (44.6)	0.000
The number of metabolic syndrome risk factors	1.95 (1.4)	1.8 (1.4)	2.2 (1.4)	0.000
Having metabolic syndrome	2304 (34.3)	1375 (30.9)	929 (41.1)	0.000

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

A1c (HbA1c ≥ 5.7%) was used as a substitute biomarker for abnormal blood glucose, an indicator that has been used previously in determining metabolic syndrome (Ong et al., 2010; Siu and Yuen, 2014). Trained ATP staff assessed anthropometrics and blood pressure (Ye et al., 2017). Waist circumference was assessed at the highest point of the hip, with one layer of clothing, and recorded to the nearest 0.1 cm. Two measurements were taken, and a third measure was taken if their differences exceeded 1 cm. The average of the two closest measurements was used. The Omron® HEM907XL IntelliSense Automated Professional Digital Blood Pressure Monitor (Omron; Kyoto, Japan) was employed to measure systolic and diastolic blood pressure. The first blood pressure measurement was taken while seated after at least 5 min of rest, followed by two more measurements 2 min apart to estimate average blood pressure. Blood samples of 50 mL were collected from participants in the non-fasting state. On-site processing was available for the majority of collections, and therefore aliquots were frozen at −80 °C within 2 h of the collection; when on-site processing was not available, samples were shipped overnight at 4 °C to the ATP lab in Calgary, where they were processed and frozen to −80 °C within 24 h of collection. From 2017 to 2020, these samples were transferred to a clinical diagnostic lab (Calgary Lab Services, Calgary, Alberta) to analyse a panel of clinical markers. Briefly, a serum lipid panel (total cholesterol, HDL-cholesterol, and triglyceride) was conducted on a Cobas 8000 System using colourimetric and enzymatic methods, and HbA1c was analysed from red blood cells on a Cobas C513 system using an immunoturbidimetric method. The mentioned physical measures and biological samples were used to determine the presence of metabolic syndrome (binary outcome) and the frequency of metabolic syndrome components (count outcome) to be included in the analysis.

Residential neighbourhood greenness and built attributes. Similar to previous studies (de Bont et al., 2020; Huang et al., 2020), NDVI was used to quantify levels of neighbourhood greenness. The NDVI was calculated using the Landsat 5 satellite imagery for the Alberta region obtained from the Canadian Urban Environmental Health Research Consortium (CANUE) (The website of CANUE: https://canue.ca) (The Canadian Urban Environmental Health Research Consortium, 2018). CANUE data was linked to participants' postal codes to provide neighbourhood environment estimates. Google Earth Engine® and MATLAB® software were applied to assess the pixel-based mean NDVI values (Gorelick et al., 2017; The Math Works, 2018). The average NDVI of all pixels within each 1000 m buffer was calculated. Neighbourhood built attributes, including dwelling density, intersection density,

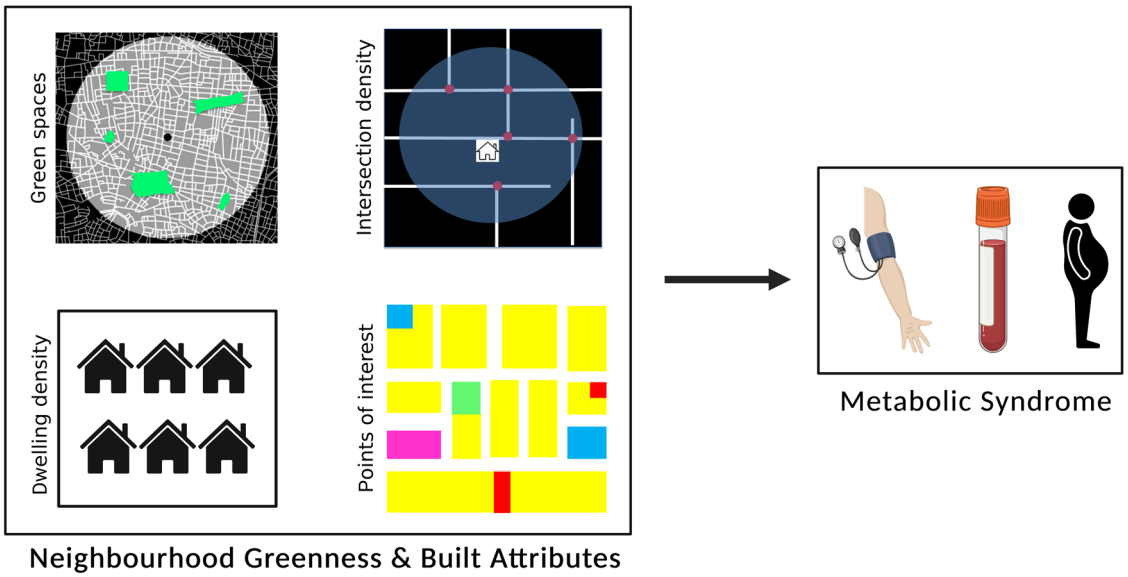

Fig. 2 Exposures and outcome in this study (Part of the figure was created with BioRender.com).

and points of interest, were obtained from CANUE from their Canadian Active Living Environments (ALE) 2016 dataset. The full details and procedure for developing the Can–ALE attributes have been documented elsewhere (Herrmann et al., 2019; Ross et al., 2018). Briefly, each variable was calculated using geographic information systems (GIS) within a one-kilometre Euclidean buffer around the centroids of dissemination areas (the smallest geographic census areas used in Canada). The dwelling density, intersection density, and points of interest were defined as the number of three-ways or more intersections, dwellings, and points of interest per square kilometre in the buffer, respectively. The points of interest were derived from OpenStreetMap and included a range of walking destinations such as schools, shops, and places of business (Ross et al., 2018). All postal codes within a dissemination area were assigned the same value for the Can-ALE attributes. The NDVI and built attributes were standardised before the analysis. In line with several previous studies (Hajna et al., 2021; Koohsari et al., 2021), the ALE index was measured by summing the *z*-scores (estimated based on our sample) of the three walkable built attributes with equal weight given to each attribute. The NDVI was negatively correlated with the ALE index ($r = -0.48$) and was not included in the index developed by the original authors (Herrmann et al., 2019; Ross et al., 2018); thus, we excluded the NDVI from the index (Fig. 2).

Covariates. Participants reported several sociodemographic characteristics, including age, sex, marital status, highest education level achieved, ethnicity, employment status, and annual household income. Current smoking status was also included as a covariate due to its association with metabolic syndrome (Cena et al., 2011).

Statistical analysis. Descriptive statistics, including frequencies and measures of central tendency and variation, were computed for covariates, metabolic syndrome and its components, NDVI, and built attributes. Independent t-tests and Pearson's chi-square test were employed to compare variables between women and men. Covariate-adjusted ordinal logistic regression was used to estimate the associations between NDVI, built attributes (dwelling density, intersection density, number of points of interest, ALE index) and the number of metabolic syndrome components (b = unstandardised regression coefficients and 95% CI). Covariate-adjusted logistic regression analysis was conducted to estimate the odds ratios (ORs) and 95% confidence intervals (CIs) for the associations between NDVI, built attributes, and the presence of metabolic syndrome. Each NDVI and built attribute was examined in separate models. The interactions between the NDVI and built attributes with sex were also tested. When the interaction term was significant, sex-stratified analyses were conducted. Given the low percentage of missing data for our variables of interest, a complete-case analysis was performed (Jakobsen et al., 2017). All inferential statistical tests were two-tailed, and statistical significance was established at $p < 0.05$. Analysis was undertaken using Stata 15.0 (Stata Corp., College Station, TX, US).

Table 2 Participants' neighbourhood NDVI and walkable built attributes.

	Total ($n = 6718$) Mean (SD)	Women ($n = 4455$) Mean (SD)	Men ($n = 2263$) Mean (SD)	p^a
NDVI	0.3 (0.1)	0.3 (0.1)	0.3 (0.1)	0.003
Dwelling density	881.0 (568.4)	881.8 (563.9)	879.3 (577.2)	0.864
Intersection density	30.7 (14.7)	30.6 (14.8)	30.8 (14.5)	0.613
Points of interest	47.9 (41.4)	47.8 (41.1)	48.2 (41.9)	0.707
Active Living Environment Index	0.1 (2.5)	0.1 (2.5)	0.1 (2.5)	0.779

[a]Based on an independent *t*-test.

Results

Table 2 shows the participants' neighbourhood NDVI and built attributes. There were no significant differences ($p < 0.05$) in the neighbourhood built attributes between women and men. The average neighbourhood NDVI was higher for women than men ($p < 0.05$).

Table 3 shows the associations between NDVI and built attributes with the number of metabolic syndrome risk factors

Table 3 Associations between NDVI, walkable built attributes with the number of metabolic syndrome risk factors and the odds of being classified as having metabolic syndrome.

	The number of metabolic syndrome risk factors	Having metabolic syndrome
	β (95% CI)	OR (95% CI)
NDVI	−0.00 (−0.05, 0.04)	1.00 (0.95, 1.06)
Dwelling density	−0.05 (−0.09, −0.01)*	0.95 (0.90, 1.01)
Intersection density	−0.03 (−0.08, 0.01)	0.95 (0.90, 1.00)
Points of interest	−0.11 (−0.16, −0.07)**	0.89 (0.84, 0.94)**
Active Living Environment Index	−0.03 (−0.05, −0.01)**	0.97 (0.95, 0.99)**

All models were adjusted for age, sex, 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. NDVI and walkable built attributes were standardised (i.e., *z*-scores) prior to the analysis.
OR odds ratio, *CI* confidence interval.
**$p < 0.02$.
*$p < 0.05$.

and the odds of having metabolic syndrome. Dwelling density and points of interest were negatively associated with the number of metabolic syndrome risk factors ($b = -0.05$, 95% CI −0.09, −0.01, $p = 0.040$ and $b = -0.11$, 95% CI −0.16, −0.07, $p < 0.001$, respectively). Points of interest were positively associated with lower odds of having metabolic syndrome (OR = 0.89, 95% CI 0.84, 0.94, $p < 0.001$). An increase in the ALE index was negatively associated with the number of metabolic syndrome risk factors ($b = -0.03$, 95% CI −0.05, −0.01, $p = 0.001$) and associated with lower odds of having metabolic syndrome (OR = 0.97, 95% CI 0.95, 0.99, $p = 0.005$). Sex-by-built attribute interactions estimated in relation to metabolic syndrome were only significant for points of interest: points of interest were positively associated with the number of metabolic syndrome risk factors in women ($b = -0.08$, 95% CI −0.14, −0.03, $p = 0.003$) and men ($b = -0.18$, 95% CI −0.26, −0.10, $p < 0.001$). No significant associations were found for NDVI or intersection density in relation to the metabolic syndrome outcomes.

Discussion

Using data from a relatively large sample of Canadian adults, this study examined the associations between the neighbourhood built environment and metabolic syndrome and the number of metabolic syndrome clinical risk factors. Similar to some previous studies (Coffee et al., 2013; Daniel et al., 2019; Dengel et al., 2009; Tsiampalis et al., 2021), our study found that neighbourhood built environment attributes were associated with metabolic syndrome. In an earlier study, we found that space syntax walkability was significantly associated with some individual cardiometabolic risk factors (Koohsari et al., 2023). However, the source and nature of the built environment measures remain identical in both studies. Furthermore, the outcome measure (metabolic syndrome) represents a novel metric that surpasses the scope of the earlier paper's objectives. Our findings support those of other studies in Canada (McCormack et al., 2019) and elsewhere (Koohsari et al., 2020; Leal and Chaix, 2011; Malambo et al., 2016), suggesting the neighbourhood built environment is associated with modifiable risk factors for cardiovascular diseases.

In our study, a supportive neighbourhood active living environment was associated with having fewer metabolic syndrome risk factors and lower odds of metabolic syndrome. Notably, our finding corresponds with other studies that have found adults residing in neighbourhoods of higher walkability, estimated based on indexes derived from the aggregating scores for individual attributes (e.g., density, street connectivity, and land use), to have a lower likelihood of metabolic syndrome (Coffee et al., 2013). Moreover, we found a protective association between a supportive neighbourhood active living environment and metabolic syndrome. This finding contributes to the growing number of other Canadian studies that have found associations between the ALE index with physical activity and health outcomes (Colley et al., 2019a, b; Keats et al., 2020; Mah et al., 2020). For example, in another study conducted in Canada, significant positive associations have been reported between the quintiled ALE index with self-reported daily minutes of transport-related (but not recreational physical activity) (Colley et al., 2019a), with accelerometer-measured moderate to vigorous physical activity (Colley et al., 2019a), and with daily leisure walking-related energy expenditure among adults (Mah et al., 2020). Herrman et al. (2019), in an ecological study including national data (i.e., dissemination areas as the unit of analysis), reported moderate-to-strong correlations between the ALE index (including the transit attribute) and walking to work ($r = 0.47$) and active transport to work ($r = 0.78$). In their cross-sectional analysis with data collected from Atlantic provinces, Keats et al. (2020) found that residing in neighbourhoods with less supportive active living environments was associated with a higher likelihood of depression and cancer (excluding skin cancer) but not with diabetes, cardiovascular diseases, chronic respiratory conditions, or multi-morbidities. Moreover, Colley et al. (2019b), in a cross-sectional analysis of national data, found negative trends between the ALE index with body mass index and the percentage of overweight and obesity in young and middle-aged adults. Together with previous evidence, our study findings suggest that neighbourhoods with a more supportive active living environment (or walkability) may promote health and reduce chronic disease.

In addition to the ALE index, we found that the number of points of interest in the neighbourhood was associated with fewer metabolic syndrome risk factors and lower odds of metabolic syndrome. Furthermore, in our study, higher dwelling density was associated with having fewer metabolic syndrome risk factors. The direction of this association was the same for women and men, although the magnitude of the association was higher for men. Since men and women are exposed to the same built environment attributes, changing the built environment may be considered a universal intervention. However, interactions with the built environment attributes, behavioural preferences, and the impact of these attributes on the health of men and women may sometimes be different (Valson and Kutty, 2018). These built environment attributes have the potential to impact metabolic syndrome through various pathways, including influences on physical activity and sedentary behaviour (Koohsari et al., 2020; Leal and Chaix, 2011; Nieuwenhuijsen, 2018). Numerous studies have highlighted the importance of having different destinations nearby to support physical activity, particularly transportation-related walking (Kärmeniemi et al., 2018; McCormack and Shiell, 2011). Moreover, in support of our findings, positive correlations between ALE attributes, including the number of points of interest and dwelling density with walking to work and active commuting to work (via walking, bicycling, or public transit) have been found in Canada (Herrmann et al., 2019).

In contrast with some previous studies (de Keijzer et al., 2019; Yang et al., 2020), we observed no significant association between the greenness measure (mean NDVI) and metabolic syndrome. The reasons for our null findings between residential greenness and metabolic syndrome remain speculative. It may be that the associations between environmental factors and metabolic syndrome are conveyed through transportation-related physical activity instead of recreational walking in parks and green spaces.

Alternatively, it may be that our measure of residential greenness cannot truly represent the amount and the variability of greenspaces to which residents are exposed (Pereira et al., 2012) or that greenspace-related features other than vegetation coverage (i.e., quality, size, amenities, and features) may be essential factors (de Keijzer et al., 2019). Differences in study and sample characteristics may also explain why our finding was not congruent with previous studies. For instance, de Keijzer et al. (2019) examined incident cases of metabolic syndrome over a 15-year follow-up, which involved four repeat measures of exposure (greenness) in a sample of UK civil servants (about 73% male) from urban and rural areas. Our study included a cross-sectional analysis of prevalent cases with a sample derived from the general population. Future studies must explore these associations using a comprehensive list of greenness measures.

This study has some limitations. The cross-sectional nature of our study precludes the drawing of causal relationships from our findings. Our greenery measure, NDVI, does not differentiate the quality and type of green spaces and, therefore, may underestimate the potential effect of green space on preventing or reducing metabolic syndrome. The built environment variables included in our study are typically shown to be associated with transportation-related physical activity (Herrmann et al., 2019; Kärmeniemi et al., 2018). However, there may be other built environment variables associated with other relevant health behaviours (e.g., diet) that are important to consider in relation to metabolic syndrome (e.g., availability of fast-food restaurants, supermarkets and convenience stores) (Dengel et al., 2009; Tsiampalis et al., 2021). Future studies also can investigate how different categories of points of interest, such as parks, schools, and hospitals, are associated with metabolic syndrome. Residential self-selection may influence the estimated associations between built attributes and metabolic syndrome, as it involves the possibility of healthier individuals choosing to reside in neighbourhoods that support their health or behavioural preferences. The risk of disease is on a continuum (Rose, 2001); the binary classification of metabolic syndrome (yes/no) ignores that even those who did not meet the criteria for metabolic syndrome still likely carry some risk of cardiometabolic disease. The information on specific medication use was missing in this study which may confound the findings. Some participants were likely being treated for conditions associated with metabolic syndrome (e.g., receiving medication for hypertension, hyperglycaemia, and hyperlipidemia), resulting in an underestimation of metabolic syndrome prevalence and the average number of metabolic syndrome risk factors in our sample. This misclassification would attenuate the associations between the built environment and metabolic syndrome towards the null. Thus we consider our estimates of these associations to be conservative. The large sample size, adding to the precision of our study's estimates, the testing of sex as an effect modifier, and the inclusion of built environment attributes used in other Canadian studies (i.e., ALE index) are strengths of our study. Study participants were situated in urban areas across an entire Canadian province, representing different neighbourhood contexts and sociodemographic and health profiles, increasing the external validity of our findings.

Conclusions

Given the growing awareness of the impact of built environments on cardiometabolic health, we investigated the associations between various built environment attributes and metabolic syndrome in a sample of adults in Canada. The following major conclusions were drawn:

- Our study provided empirical evidence on the supportive role of activity-friendly neighbourhoods on metabolic health: living in areas with a higher number of destinations, dwelling density, and total active living-environment friendliness was associated with better metabolic health.
- No significant associations were found between residential greenness (measured by NDVI) and metabolic syndrome in our sample. Further research is needed to explore other residential greenness measures in relation to metabolic syndrome.
- This evidence helps inform policy and practice, especially for those interested in promoting population health. However, findings from non-Canadian studies are needed to inform the local context due to geographical, climatic, political, health care, and cultural disparities among countries. For example, the local climate is a key factor affecting the environmental comfort of the same built environment attributes (Ren et al., 2022).

Data availability

The data supporting the findings of this study are sourced from Alberta's Tomorrow Project (ATP), but access to these data is subject to restrictions. The data used in the current study were obtained under a license and are not publicly accessible. However, interested parties may request access to the data from the authors, subject to reasonable request and with the permission of Alberta's Tomorrow Project (ATP).

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Author contributions

MJK: Conceptualisation, Methodology, Writing—Original draft preparation. AY: Methodology, Writing—Reviewing and Editing. KO: Methodology, Writing—Reviewing and Editing. TN: Methodology, Writing—Reviewing and Editing. YN: Writing—Reviewing and Editing. JV: Methodology, Writing—Reviewing and Editing. GRM: Supervision, Methodology, Writing—Reviewing and Editing.

Competing interests

The authors declare no competing interests.

Ethical approval

This study was approved by the University of Calgary Conjoint Health Research Ethics Board (REB19-1992).

Informed consent

Written consent was obtained from all participants.

Additional information

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