Neighbourhood walkability and pedometer and accelerometer-assessed walking in Canadian adults

Samantha Hajna

Department of Epidemiology, Biostatistics and Occupational Health

McGill University
Montreal, Quebec

March 2016

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Doctor of Philosophy in Epidemiology

DEDICATION

To my dearest Mom and Dad, Jaroslav and Šárka Hajna.
Thank you for your endless love, encouragement, and support.
I love you more than words can express.

And in memory of my beautiful sister Andrea
and my loving grandma Babička Marie.

Above all to my Heavenly Father.
You are my Light, my Strength, my Song.

Not to us, Lord, not to us
but to your Name be the glory,
because of your love and faithfulness.
~ Psalm 115:1 ~

ABSTRACT

Background

Urban planners consider walkable neighbourhoods to be ones characterized by a variety of services and destinations easily accessed through well-connected street networks. Such walkable neighbourhoods tend to emerge in more densely populated areas where demand for services is high. Residents of more walkable neighbourhoods report higher levels of utilitarian walking (i.e., walking for a specific purpose like to get to work) compared to residents of less walkable neighbourhoods. The relationship between neighbourhood walkability and objectively assessed total walking is less clear, both in general adult and in sedentary chronic disease populations.

Objectives

The objective of my thesis was to determine if neighbourhood walkability (based on Geographic Information System (GIS)-derived street connectivity, land use mix and population density) is associated with higher levels of accelerometer or pedometer-assessed total walking in the general Canadian adult population and in adults with type 2 diabetes - a population that may be particularly sensitive to features of neighbourhood environments.

Methods

I conducted six complementary studies. My ***first*** study (*Manuscript 1*) was a systematic review and meta-analysis. In this study I summarized the results of the previous studies that have been conducted on the association between GIS-derived neighbourhood walkability and biosensor-assessed daily steps in adults. My ***second*** and ***third*** studies (*Manuscripts 2* and *3*) were

methodological pieces in which I assessed the validity of the walkability measures that I used in my three main substantive studies (*Manuscripts 4, 5* and *6*). In my ***fourth*** study (*Manuscript 4*), I investigated the associations of GIS-derived neighbourhood walkability and the publicly available Walk Score® with accelerometer-assessed walking and participant-reported utilitarian walking in 2,949 adults who participated in Cycle 1 (2007-2009) of the Canadian Community Health Survey. In my ***fifth*** study (*Manuscript 5*) I investigated how GIS-derived neighbourhood walkability and three other measures of walkability (i.e., in-field audits, the Walk Score® and participant-reported measures) were associated with pedometer-assessed walking in a sample of adults with type 2 diabetes. While I had multiple measures of walkability in this study, I did not have information on where this walking occurred. I hypothesized that a mismatch between neighbourhood walkability and walking may have underestimated the true association. In my ***sixth*** study (*Manuscript 6*), I utilized integrated Global Positioning System (GPS)-accelerometer technology in a sample of adults with type 2 diabetes to determine if neighbourhood walkability was associated with total physical activity occurring specifically within home neighbourhoods.

Results

Manuscript 1 – Based on studies from Belgium, the Czech Republic and Japan, I demonstrated that adults who live in high compared to low walkable neighbourhoods accumulate 766 more steps/day (95% credible interval (CrI) 250, 1271). This accounts for approximately 8% of recommended daily steps. These findings support the hypothesis that higher neighbourhood walkability is associated with higher levels of biosensor-assessed walking in adults. Comparable studies, however, have yet to be conducted in North America. Estimating this association in

Canada was the objective in my three substantive studies (*Manuscripts 4, 5* and *6*). **(Hajna et al., *BMC Public Health*, 2015; 15:768)**

Manuscript 2 – Based on data collected from a cohort of adults with type 2 diabetes living in Montreal (QC, Canada), I demonstrated that the correlation between GIS-derived and audit-assessed neighbourhood walkability was high (R: 0.7, 95% confidence interval (CI) 0.6, 0.8) but the correlations between objective (GIS-derived and audit) and participant-reported measures of walkability were low (R: 0.2, 95% CI 0.04, 0.3 and R: 0.2, 95% CI 0.06, 0.3, respectively). These results indicate that use of GIS-derived measures, as I did in *Manuscripts 4, 5* and *6*, is reasonable in place of more labor-intensive audits. The results of this study also indicate that participants' perceptions of neighbourhood walkability appear to capture a different aspect of walkability than researcher-assessed measures. This led me to also consider the independent associations of perceived neighbourhood walkability on walking/physical activity when these data were available (*Manuscripts 5* and *6*). **(Hajna et al., *Am J Prev Med.* 2013; Jun;44(6):e51-52)**

Manuscript 3 - I found evidence in the literature that the formula commonly used to calculate land use mix – a component of neighbourhood walkability - was misspecified in previous studies. I demonstrated that misspecification of the Shannon entropy formula may systematically underestimate the true association between land use mix and walking by 26.4% (95% CI 25.8, 27.0). To minimize measurement bias, use of a constant denominator in the entropy formula is required. I ensured that the correct version of this formula was applied in my three substantive pieces (*Manuscripts 4, 5* and *6*). **(Hajna et al., *Health & Place,* 2014; 29: 79-83)**

Manuscript 4 – In a large cohort of Canadian adults, there was a positive graded association between neighbourhood walkability and odds of walking ≥1 hour/week for utilitarian purposes (Q4 *versus* Q1 of GIS-derived walkability: OR: 1.66, 95% CI 1.31, 2.11; Q3 *versus* Q1: OR: 1.41, 95% CI 1.14, 1.76; Q2 *versus* Q1: OR: 1.13, 95% CI 0.91, 1.39). No important relationship was observed between GIS-derived walkability and daily steps. **(Hajna et al., *BMJ Open*, 2015, 5(11):e008964)**

Manuscript 5 - Adults with type 2 diabetes who perceived their neighbourhoods to be the most walkable completed 1345 more steps/day (95% CrI 718, 1976; Quartiles 4 *versus* 1). Adults living in the highest quartile of neighbourhood walkability achieved 606 more steps/day (95% CrI 8, 1203) than people living in the lowest quartile of neighbourhood walkability. These results, however, were inconclusive and not graded across quartiles. In this study, data on self-reported utilitarian walking were not available. **(Hajna et al., *PLoS One*, In Press, doi: 10.1371/journal.pone.0151544)**

Manuscript 6 - There was a positive relationship between GIS-derived neighbourhood walkability and neighbourhood-based physical activity: a one standard deviation increment in walkability was associated with 10.4% of a standard deviation increment in physical activity occurring specifically within home neighbourhoods (95% CI 1.2, 19.7; adjusted for age, BMI, sex, university, season, car access, residential self-selection and valid wear-time). This association was not apparent in models that did not restrict to physical activity occurring specifically within home neighbourhoods (0.7%, 95% CI -13.7, 15.2). **(Hajna et al., *International Journal of Behavioral Nutrition and Physical Activity*, Under Review)**

Conclusions

While there is evidence from Europe and Asia that adults who live in more walkable neighbourhoods achieve higher total levels of walking, this association does not appear to hold in the Canadian context. In the Canada-wide study, no important association was found between higher neighborhood walkability and total accelerometer-assessed walking and in the study of adults with type 2 diabetes, no conclusive graded association was observed. While neighbourhood walkability may not be associated with total physical activity, there is evidence that adults living in more walkable neighbourhoods may be slightly more active within their home neighbourhoods. The results of this body of research suggest that improving neighbourhood walkability is not the "magic bullet" to achieving population-level increases in total physical activity. Other factors will need to be targeted to facilitate increases in total physical activity. Examples include reducing seasonal deficits in walking and improving perceptions of neighbourhood walkability. The results of my research also underscore the importance of accurate measurement in discerning meaningful environmental influences on health. Combining real-time monitoring of physical activity with detailed social surveying, researcher-assessed and perceived walkability measurement, and clinical measurements represents the ideal approach to studying the role of neighbourhood walkability on physical activity.

RÉSUMÉ

Mise en contexte

Les urbanistes définissent les quartiers marchables selon la variété des services et des destinations facilement accessibles par un réseau de rues bien connectées. Ce type de quartiers semble émerger dans des régions où il y a une grande densité de population et donc une demande élevée pour des services. Comparer aux résidents de quartiers moins marchables, les résidents des quartiers les plus marchables rapportent marcher davantage pour des tâches utiles (c'est-à-dire marcher avec un objectif spécifique, comme aller au travail). La relation entre le niveau de marchabilité des quartiers et des mesures objectives du niveau de marche n'est toutefois pas évidente et ce, autant au sein de la population adulte en général qu'auprès de populations atteintes de maladies chroniques.

Objectifs

L'objectif de ma thèse est de déterminer si la marchabilité d'un quartier (selon les mesures de connectivité entre les rues, de l'indice de mixité de l'utilisation du sol et de densité de la population établies avec un Système d'Information Géographique (SIG)) est associée avec le niveau de marche mesuré via des accéléromètres ou des podomètres chez la population adulte Canadienne et chez des adultes atteints d'un diabète de type 2, soit une population qui pourrait être particulièrement sensible à certaines caractéristiques des quartiers.

Méthodes

J'ai mené six études complémentaires. Ma ***première*** étude (*Manuscrit 1*) était une revue systématique et une méta-analyse. Dans cette étude, j'ai synthétisé les résultats de précédentes recherches sur l'association, chez des adultes, entre la marchabilité d'un quartier via SIG et le nombre de pas quotidiens mesuré via des biosenseurs. Les ***deuxième*** et ***troisième*** études (*Manuscrits 2* et *3*) sont des études de validation d'outils, que j'utilise dans mes trois études principales, pour mesurer la marchabilité des quartiers (*Manuscrits 4, 5 et 6*). Dans ma ***quatrième*** étude (*Manuscrit 4*), j'évalue l'association entre la marchabilité d'un quartier via SIG et le *Walk Score*®, un score publiquement disponible, avec le niveau de marche évalué par accéléromètre et le niveau de marche utile rapporté chez les 2,949 adultes qui ont participé à l'enquête sur la santé dans les collectivités canadiennes lors du premier cycle (2007-2009). Au cours de ma ***cinquième*** étude (*Manuscrit 5*), j'ai évalué si la marchabilité d'un quartier via SIG ainsi que trois autres mesures de la marchabilité (c'est-à-dire, via des audits de terrain, le *Walk Score*® et des mesures rapportées par le participant) sont associés au niveau de marche mesuré par podomètre dans un échantillon d'adultes atteints de diabète de type 2. Malgré que j'aie de nombreuses mesures de marchabilité pour cette étude, je n'avais pas d'information sur l'endroit où les gens marchaient. J'ai émis l'hypothèse qu'une mauvaise affiliation entre la marchabilité d'un quartier et le niveau de marche pouvaient sous-estimer la réelle association entre ces éléments. Dans ma ***sixième*** étude (*Manuscrit 6*), j'ai utilisé, chez un groupe d'adultes atteints de diabète de type 2, un moniteur de géo-positionnement par Satellite (GPS) couplé d'un accéléromètre pour établir si la marchabilité d'un quartier est associé à la pratique d'activité physique qui se produit spécifiquement dans ce quartier.

Résultats

Manuscrit 1 – À partir d'études publiées en Belgique, en République Tchèque et au Japon, j'ai démontré que les adultes qui habitent dans des quartiers très marchables, comparativement à des quartiers peu marchables, marchent 766 pas de plus par jour (95% intervalle de crédibilité (CrI): 250, 1271). Soit approximativement 8% du nombre de pas quotidien recommandé. Ce résultat soutien l'hypothèse qu'un quartier plus marchable est associé à davantage de pas, mesurés via des biosenseurs, chez des adultes. Toutefois des études comparables n'ont pas encore été faites en Amériques du Nord. L'objectif de mes 3 études principales était donc d'évaluer cette association au Canada (*Manuscrits 4, 5* et *6*). **(Hajna et al., *BMC Public Health*, 2015; 15:768)**

Manuscrit 2 – À partir de données collectées auprès d'un groupe d'adultes atteints de diabète de type 2 vivant à Montréal (QC, Canada), j'ai démontré que la corrélation entre la marchabilité du quartier établie par SIG et celle établie via un audit est élevé (R: 0.7, 95% intervalle de confiance (CI) 0.6, 0.8). Par contre les corrélations entre des mesures objectives (établies par SIG et par audit) et des mesures de marchabilité rapportées par les participants sont faibles (R: 0.2, 95% CI 0.04, 0.3 et R: 0.2, 95% CI 0.06, 0.3, respectivement). Ces résultats indiquent que l'utilisation de mesures de marchabilité via SIG, telles qu'utilisées dans mes *Manuscrits 4, 5* et *6*, sont adéquates en remplacement de méthodes qui exigent beaucoup de travail comme les audits. Les résultats de cette étude démontrent aussi que la perception de marchabilité d'un quartier par les participants ne mesure pas les mêmes aspects de marchabilité d'un quartier que des mesures utilisées par les chercheurs. Ceci m'a amenée à considérer l'association entre la perception de la marchabilité d'un quartier et la marche/activité physique de manière indépendante lorsque les données étaient disponibles (*Manuscrits 5* et *6*). **(Hajna et al., *Am J Prev Med.* 2013;**

Juin;44(6):e51-52)

Manuscrit 3 – Dans la littérature scientifique, j'ai constaté que la formule généralement utilisée pour calculer l'indice de mixité de l'utilisation du sol – un des éléments définissant le marchabilité d'un quartier- était mal appliquée dans plusieurs études. J'ai démontré que la mauvaise application de la formule d'entropie de Shannon pouvait résulter en une sous-estimation systématique de la réelle association entre l'indice de mixité de l'utilisation du sol et le niveau de marche de 26.4% (95% CI 25.8, 27.0). Afin de minimiser les biais associés à la mesure, l'utilisation d'un dénominateur constant dans cette formule est nécessaire. Je me suis assurée d'utiliser cette version de la formule dans mes trois études principales (*Manuscrits 4, 5* et *6*). **(Hajna et al.,** *Health & Place,* 2014; 29: 79-83**)**

Manuscrit 4 – Au sein d'une large cohorte d'adultes Canadiens, on observe une association positive par niveau entre la marchabilité d'un quartier et la probabilité de marcher pour des tâches utiles ≥1 heure/semaine (Q4 *versus* Q1 de la marchabilité estimé par GIS : rapport de cotes (RC): 1.66, 95% CI 1.31, 2.11; Q3 *versus* Q1: RC: 1.41, 95% CI 1.14, 1.76; Q2 *versus* Q1: RC: 1.13, 95% CI 0.91, 1.39). Aucune association importante entre le GIS et le nombre de pas quotidiens n'était observée. **(Hajna et al., *BMJ Open,* 2015, 5(11):e008964)**

Manuscrit 5 – Les adultes atteints de diabète de type qui perçoivent leur quartier comme ayant un niveau de marchabilité élevé marchent 1345 pas de plus par jour (95% CrI 718, 1976; Quartiles 4 *versus* 1). Les adultes vivant dans un quartier se situant dans le quartile où la marchabilité est la plus élevée font 606 pas de plus par jour (95% CrI 8, 1203) que ceux vivant dans un quartier situé dans le quartile où la marchabilité est la plus faible. C'est résultats ne sont pas concluants à travers tous les quartiles. Dans cette étude, aucune donnée sur le niveau de marche utile rapporté n'était disponible. **(Hajna et al., *PLoS One,* doi: 10.1371/journal.pone.0151544. Sous presse)**

Manuscrit 6 – Il y a une relation positive en la marchabilité d'un quartier, évalué par GIS, et la pratique d'activité physique ayant lieu dans ce quartier: une augmentation d'un écart-type dans la marchabilité était associée avec une augmentation de 10.4% d'un écart-type de l'activité physique qui est faite à même le quartier (95% CI 1.2, 19.7; ajusté pour l'âge, le sexe, l'indice de masse corporelle, la scolarité de niveau universitaire, la saison, l'accès à un véhicule, l'auto-choix de la résidence et les périodes valides de port de l'appareil). Cette association n'est pas manifeste dans des modèles où l'activité physique mesurée n'est pas limitée à celle qui est spécifiquement faite dans les quartiers habités par les participants (0.7%, 95% CI -13.7, 15.2). **(Hajna et al., *International Journal of Behavioral Nutrition and Physical Activity,* En révision)**

Conclusions

Bien qu'il y est des évidences en Europe et en Asie que les adultes qui vivent dans des quartiers plus marchables ont des niveaux plus élevés de marche, cette association ne semble pas se refléter dans le contexte Canadien. Dans l'étude pan-canadienne, aucune association importante n'a été observée entre la marchabilité d'un quartier et la marche total mesuré par accéléromètre. Dans l'étude chez les adultes atteints de diabète de type 2, aucune association par niveau n'a été observée. La marchabilité d'un quartier n'est peut-être pas associée à l'activité physique total, toutefois il existe des évidences que les adultes vivants dans des quartiers plus marchables sont légèrement plus actifs à même leur propre quartier. L'ensemble de ces résultats suggère qu'améliorer la marchabilité d'un quartier n'est pas une panacée pour amener la population à augmenter sa pratique d'activité physique totale. D'autres facteurs doivent aussi être ciblés pour augmenter la pratique d'activité physique. Par exemple, en réduisant le déficit saisonier de marche et en améliorant la perception de la marchabilité du quartier. Les résultats de mes recherches soulignent l'importance d'utiliser des mesures précises pour établir les impacts que l'environnement peut avoir sur la santé. Une combinaison de mesures en temps réel de l'activité physique avec des questionnaires détaillés, des évaluations par les chercheurs et des mesures de perceptions de la marchabilité, ainsi que des mesures cliniques, est l'approche à privilégier pour étudier le rôle de la marchabilité d'un quartier sur la pratique de l'activité physique.

THESIS FORMAT

My thesis is presented as a collection of six manuscripts of which I am the primary author. I have organized my thesis into nine chapters. In *Chapter 1* I introduce my topic and present my study objectives. In *Chapter 2*, I review the existing body of literature on the association between neighbourhood walkability and physical activity in adults. In *Chapter 3* I present the results of my systematic review and meta-analysis (*Manuscript 1*). In this manuscript I summarized the current state of knowledge on the association between neighbourhood walkability and biosensor-assessed daily steps in adults. In *Chapters 4* and *5* I present the findings of my two methodological studies (*Manuscripts 2* and *3*) in which I tested the validity of the walkability measures that I used in my three substantive pieces (*Manuscripts 4, 5*, and *6* presented in *Chapters 6, 7* and *8)*. I conclude my thesis in *Chapter 9.* In this chapter I highlight the key substantive, methodological and policy contributions of my thesis.

STATEMENT OF ORIGINALITY

Each chapter presented in my thesis represents original scholarship and advances our knowledge of the association between neighbourhood walkability and physical activity in both the general Canadian adult population and in adults with type 2 diabetes. I received guidance and feedback from my supervisors and co-authors, but all six of my studies represent my original work. I conceived the ideas for *Manuscripts 1 and 3*. *Manuscripts 2, 4, 5* and *6* were conceived as a result of discussions with my supervisors. *Manuscripts 2* and *4* were based on secondary data that were available to me when I arrived at McGill University, but I facilitated access to the data for all of the other manuscripts. For *Manuscript 4* I developed the protocol for the study and had it approved by the Social Sciences and Humanities Research Council (SSHRC). Due to sensitivity issues surrounding access to individual-level residential data, it took me an additional two years of face-to-face meetings, and email and phone conversations with individuals from Statistics Canada to get access to these data. Using these data I also conducted *Manuscript 3.* I developed and conducted *Manuscript 6*. This included designing the study, writing all aspects of the grant that secured funding for this study (funded by the Heart and Stroke Foundation of Canada in 2012), meeting with physicians to ask them to help me recruit patients into my study, going to McGill-affiliated hospitals and clinics several times per week to recruit patients, conducting medical assessments on participants one to two times per week (i.e., taking blood pressure measurements, accompanying them to get their blood drawn, etc.), downloading and processing the biosensor data, following up with participants, developing and conducting all of the data analyses, and writing and preparing the manuscript for publication. The originality of each manuscript is highlighted below.

Manuscript 1: **Hajna S, Ross N, Brazeau AS, Joseph L & Dasgupta K. Associations between neighbourhood walkability and daily steps in adults: A systematic review and meta-analysis.** ***BMC Public Health.*** **2015; 15:768.**

This is the first systematic review and meta-analysis of the studies that have quantified the association of GIS-derived neighbourhood walkability (based on street connectivity, land use mix, and/or residential/population density) with biosensor-assessed daily steps in adults. I demonstrated that a positive association exists between neighbourhood walkability and total daily steps. These results were restricted, however, to Europe and Japan. The goal of my doctoral research was to determine if the same association exists among Canadian adults.

Manuscript 2: **Hajna S, Dasgupta K, Halparin M & Ross N. Neighborhood walkability: Field validation of Geographic Information System Measures.** ***Am J Prev Med. 2013;*** **Jun;44(6):e51-52.**

Before estimating the neighbourhood walkability-walking association in Canada, I validated the measures of walkability that I would be using in my substantive pieces (*Manuscripts 4, 5* and *6*). GIS-derived measures of street connectivity, land use mix, and residential and/or population density are commonly used as measures of walkability. The construct validity of these measures, however, has not been previously reported. I assessed the validity of these measures against street-level audits and participant reports using data collected from a cohort of adults with type 2 diabetes living in Montréal (QC, Canada). I demonstrated that a strong correlation exists between GIS and audit-derived measures of neighbourhood walkability, indicating that GIS-derived measures of walkability can be used in place of more labor-intensive neighbourhood audits. I also demonstrated that the correlations between objective (GIS-derived and audit) and participant-reported (i.e., perceived) measures are low. When data on perceived neighbourhood walkability were available, I therefore also sought to understand its independent association with daily steps (Manuscript 5).

Manuscript 3: **Hajna S, Ross N, Joseph L & Dasgupta K. A call for caution and transparency in the calculation of land use mix: Measurement bias in the estimation of associations between land use mix and physical activity. *Health & Place.* 2014; 29: 79-83.**

One of the main components of neighbourhood walkability that I proposed to use in my substantive studies (*Manuscripts 4, 5* and *6*) was land use mix. The Shannon entropy formula is commonly used to calculate land use mix and is the method that I also proposed to use. Upon reviewing the literature, I found evidence that this formula has been misspecified in previous studies. My study is the first to draw attention to this potential source of bias and to encourage researchers to use caution and transparency in the calculation of this measure. It was also a key step in helping me understand the subtleties of this measure and how it should be properly applied in my own research.

Manuscript 4: **Hajna S, Ross N, Joseph L, Harper S & Dasgupta K. Neighborhood walkability, daily steps, and utilitarian walking in Canadian adults. *BMJ Open.* 2015, 5(11):e008964**

This was the first study to estimate the association of GIS-derived neighbourhood walkability (based on street connectivity, land use mix, and population density) with both biosensor-assessed walking and participant-reported utilitarian walking in a large sample of Canadian adults. The primary strengths of this study included assessment of daily steps using accelerometers and the inclusion of a wide variety of neighborhoods from across Canada.

Manuscript 5: **Hajna S, Ross N, Joseph L, Harper S & Dasgupta K. Neighbourhood walkability and daily steps in adults with type 2 diabetes. *PLoS One*. In Press. doi: 10.1371/journal.pone.0151544.**

This was the first study to estimate the association between neighbourhood walkability (GIS-derived, participant-reported, in-field audits, and the Walk Score®) and biosensor-assessed walking in a clinical population of adults with type 2 diabetes. Strengths of this study included multiple measures of walkability and objective assessments of walking.

Manuscript 6: **Hajna S, Kestens Y, Joseph L, Daskalopoulou S, Thierry B, Bacon S, Gauvin L, Ross N, & Dasgupta K. Neighbourhood walkability and neighbourhood-based physical activity: An observational study of adults with type 2 diabetes. *International Journal of Behavioral Nutrition and Physical Activity, Under Review*.**

Linking neighbourhood walkability to physical activity that does not necessarily occur in the residential neighbourhood may be diluting the associations. My study it the first to use GPS and accelerometer technology integrated into a single unit to determine if neighbourhood walkability is associated with neighbourhood-based total physical activity in adults with type 2 diabetes.

CONTRIBUTION OF AUTHORS

The topic, objectives, and methods of my thesis were developed in collaboration with my supervisors, Dr. Kaberi Dasgupta and Dr. Nancy A. Ross. I wrote all components of the thesis including the introduction, the literature review, the individual manuscripts, linking chapters and the concluding chapter. Dr. Dasgupta and Dr. Ross provided me with guidance throughout the research process and feedback on all drafts of my thesis and manuscripts. I am the lead author on all of the manuscripts included in this thesis. The contributions of each of my co-authors are outlined below.

Kaberi Dasgupta, MD, MSc, FRCPC is an Associate Professor of medicine at McGill University and Physician-Scientist at the McGill University Health Centre. As my primary supervisor, Dr. Dasgupta oversaw all aspects of the thesis and manuscript preparation, including the development of the methods, the interpretation of the results, and the editing of the final written material.

Nancy A. Ross, PhD is an Associate Professor in the Department of Geography and an Associate Member in the Department of Epidemiology at McGill University. As my co-supervisor, Dr. Ross oversaw all aspects of the thesis and manuscript preparation, including the development of the methods, the interpretation of the results, and the editing of the final written material.

Lawrence Joseph, PhD is a Professor in the Department of Epidemiology and Biostatistics at McGill University and a medical scientist in the Division of Clinical Epidemiology. As a thesis committee member Dr. Joseph was actively involved in the development of the statistical methodologies and provided guidance on the statistical analyses.

Sam Harper, PhD is an Assistant Professor in the Department of Epidemiology and Biostatistics. As a thesis committee member Dr. Harper was involved in the development of the thesis protocol and provided guidance in the interpretation of the results of *Manuscripts 4* and *5*.

Simon Bacon, PhD is an Assistant Professor in the Department of Exercise Science at Concordia University. As a thesis committee member Dr. Bacon was involved in the development of the thesis protocol and as a co-investigator on the Heart and Stroke grant that funded my sixth study, Dr. Bacon was also involved in the development of this study's protocol and reviewed and edited *Manuscript 6* for content.

Yan Kestens, PhD is an Associate Professor in the Department of Social and Preventive Medicine at the University of Montreal. As a co-investigator on the Heart and Stroke grant that funded my sixth study (NCT01475201) and the developer of the GPS-accelerometer units that I used to assess location-based physical activity, Dr. Kestens was actively involved in the development in the protocol for this study and provided guidance in the processing, analysis and interpretation of the geospatial and physical activity data. He also reviewed and edited *Manuscript 6* for content.

Benoît Thierry, MSc is an Engineer and Geomatics expert working at the Spatial Health Research Lab at the University of Montreal. Benoît provided ongoing technical support in the collection and management of the multi-sensor data collected as part of my sixth study. He converted the raw GPS and accelerometer data into a usable format and provided guidance in the interpretation of these data. As a co-author, Benoît also reviewed and edited *Manuscript 6* for content.

Anne-Sophie Brazeau, PhD is a post-doctoral researcher at McGill University working in the Division of Clinical Epidemiology under the supervision of Dr. Kaberi Dasgupta. Dr. Brazeau assisted in the screening and review of articles to be included in my meta-analysis (*Manuscript 1*) and reviewed and edited the final manuscript for content.

Patrcik Bélisle, MSc is a Research Associate at McGill University in the Division of Clinical Epidemiology. As a co-author of *Manuscript 1*, Patrick assisted with statistical programming and reviewed and edited the final manuscript for content.

Stella Daskalopoulou, MD PhD is an Associate Professor in the Department of Medicine at McGill University and physician-scientist at the McGill University Health Centre. As a co-investigator on the Heart and Stroke grant that funded my sixth manuscript, Dr. Daskalopoulou was involved in the development in this study's protocol and reviewed and edited the final manuscript for content.

Lise Gauvin, PhD is a Full Professor in the Department of Social and Preventative Medicine at the University of Montreal, a researcher at the Research Center of the Centre Hospitalier de l'Université de Montréal, and an associate researcher at the Léa-Roback Center on Social Inequalities of Health. As a co-investigator on the Heart and Stroke grant that funded my sixth study, Dr. Gauvin was involved in the development of this study's protocol and reviewed and edited *Manuscript 6* for content.

Max Halparin, MSc was a graduate student in the Department of Geography at McGill University during 2010. Working under the supervision of Dr. Nancy A. Ross, Max conducted the in-field neighbourhood audits and derived the GIS measures that were used in *Manuscripts 3* and *4*.

Mark Sherman, MD, FRCPC is an Associate Professor in the Department of Medicine at McGill University and Interim Director of the Division of Endocrinology at the McGill University Health Centre. As a collaborator on the CIHR-funded randomized control trial (Principal Investigator: K. Dasgupta, MOP-79275) on which my sixth study was based, Dr. Sherman played an important role in recruiting participants into my sixth study and reviewed and edited *Manuscript 6* for content.

Luc Trudeau, MD, FRCPC is an Assistant Professor of Medicine at McGill University and Director of the Hypertension Clinic at the Jewish General Hospital. As a collaborator on the CIHR-funded randomized control trial (Principal Investigator: K. Dasgupta, MOP-79275) on which my sixth study was based, Dr. Trudeau played an important role in recruiting participants into my sixth study and reviewed and edited *Manuscript 6* for content.

Rémi Rabasa-Lhoret, MD, PhD is an Associate Professor in the Department of Nutrition at the University of Montreal and Director of the Metabolic Diseases Research Unit at the Institut de Recherches Cliniques de Montréal (IRCM). As a collaborator on the CIHR-funded randomized control trial (Principal Investigator: K. Dasgupta, MOP-79275) on which my sixth study was based, Dr. Rabasa-Lhoret played an important role in recruiting participants into my sixth study and reviewed and edited *Manuscript 6* for content.

Leslie Meissner, MD, FRCPC is a physician at the McGill University Health Centre and at St. Mary's Hospital. As a collaborator on the CIHR-funded randomized control trial (Principal Investigator: K. Dasgupta, MOP-79275) on which my sixth study was based, Dr. Meissner played an important role in recruiting participants into my sixth study and reviewed *Manuscript 6*.

There were 48 other physicians who helped me recruit patients into my sixth study. Although they were not included as authors, I would like to acknowledge their roles and thank them for their help in making this study a success. They include Dr. Sabiha Awan, Dr. Alexis Baass, Dr. Jean-Marie Boutin, Dr. Candace Lee, Dr. Carolina Capelle, Dr. Joanna Caron, Dr. Stravroula Christopolous, Dr. Karen Dahan, Dr. Maxine Dumas-Pilon, Dr. Roy Eappen, Dr. Leah Feldman, Dr. Natasha Garfield, Dr. Dominique Garrell, Dr. Lawrence Green, Dr. Walter Gregory, Dr. Wen Hu, Dr. Sofia Hussaini, Dr. John Hughes, Dr. Catherine Kudo, Dr. April Kinghorn, Dr. Evelyn Kyle, Dr. Leonora Lalla, Dr. Andrea Lalonde, Dr. Pierre Larochelle, Dr. Khue Ly, Dr. Richard Mackler, Dr. Agnieszka Majdan, Dr. Goldie Marmor, Dr. Sara Meltzer, Dr. Hortensia Mircescu, Dr. David Morris, Dr. Kimberly Munro, Dr. Vivian Petropoulos, Dr. Barry Posner, Dr. Brent Richards, Dr. Juan Rivera, Dr. Ghislaine Roederer, Dr. David Morris, Dr. Samantha Sacks, Dr. Alicia Schiffrin, Dr. David Shannon, Dr. Raymond Sorge, Dr. Donald Sproule, Dr. Susan Still, Dr. Robert Wistaff, Dr. Mark Yaffe, Dr. Jean-Francois Yale and Dr. Hans Zingg.

Other individuals who were involved in my studies but were not listed as co-authors included Deborah Chan (assisted with data management for *Manuscripts 2, 5, 6*), Alexandre Poisson and Elizabeth McNamee (helped conduct the in-field audits for *Manuscript 2*), Camille O. Dallaire and Ruilan Shi (tutored me in the use of GIS for *Manuscript 5*), Paul A. Peters (facilitated access to the Statistics Canada's spatial data that I used in *Manuscripts 3* and *5*), and Colin Stewart (retrieved the Walk Scores® that I used in *Manuscripts 5*).

ACKNOWLEDGEMENTS

I would like to first extend my sincerest gratitude to my supervisor, Dr. Kaberi Dasgupta, and to my co-supervisor, Dr. Nancy A. Ross. Thank you for your ongoing support, encouragement and mentorship. It has been an absolute privilege to work with you. Your passion and dedication for the work that you do, the care and commitment that show towards your students and colleagues, and your generosity with your time are inspirational and am truly grateful for all that you have taught me. Thank you for these wonderful six years.

I would also like to thank my supervisory committee for all of their guidance and insightful discussions. I have learned so much from each of you. A special thank you to Dr. Lawrence Joseph for all of the time that you have so generously given to me.

A big thank you to all of my professors, friends, and colleagues at McGill University’s Division of Clinical Epidemiology, the Department of Epidemiology, and the Department of Geography, and at the University of Montreal. There are too many of you to name, but know that I am grateful for each of you. Dr. James Hanley, thank you for giving me the opportunity to work with you. You have taught me so much and sparked my interest in the history of medicine. I have thoroughly enjoyed every meeting with you. Dr. Mélanie Henderson, thank you for your friendship and encouragement along this journey – your support has meant so much to me. Also a special thank you to Deborah Chan for your help with recruitment and data management, Patrick Bélisle for your help with computer programming, Benoît Thierry for your help with

GPS data processing, and Dr. Anne-Sophie Brazeau for your encouragement and many tea dates. It has been a pleasure to work alongside each of you.

Last but not least, I would like to extend my sincerest gratitude to my family and friends. Mami a Tatko, thank you from the bottom of my heart for your endless love and encouragement and for all of the sacrifices that you have made for me along the way. From moving across the globe to working long hours every day, you have always supported me, loved me, and encouraged me to pursue my dreams. I love you more than words can express. Hans, what a blessing you have been to me. Thank you for your love and support. To my family overseas – Babičko Vendo, Teto Jiřinko, Strejdo Františku, Ondro, Hanko, Kamilko, Ondrášku, Teto Věro, Dědo Stando, Uncle Janusz, Aunt Charlotte and Sabina, Teto Maruško, Masina and Tom, my entire Hajna family – and to my friends and family in Canada – Sue and Jer, Opal, Rebekah, Kyrie and François, Sylvie and Max, Julie and Tim, Becky and John, Sonia and James, Marina, Bonnie, Patricia, Mrs. Rivers, Grandma and Grandpa Otten, Uncle Jim and Aunt Janice and family, Uncle Bob and Aunt Mary, Luba and Miro, Uncle John and Aunt Marjorie, Jaco and Shida and family, Jackie and Steve and family, Bob Presseau, and all of my CU20 and McGill friends. Thank you for your love and encouragement over the years. You are a joy to know and have made this journey so much fun. Above all, thank you to my Heavenly Father and Saviour Jesus Christ. To You be all the glory and honour.

STATEMENT OF SUPPORT

Financial support was granted to me by the Canadian Institutes of Health Research (CIHR) through a Doctoral Research Award (2012-2015). I also received support through a Quebec Inter-University Centre for Social Statistics Matching Grant (2012), a CIHR Interdisciplinary Capacity Enhanced Team Grant Award (2011 & 2012), a Graduate Excellence Fellowship from the Department of Epidemiology, Biostatistics and Occupational Health (2011-2012), a Graduate Studentship from the Research Institute of the McGill University Health Centre (2011-2012), a Max E. Binz Fellowship from Department of Medicine (2011-2012), a Provost's Graduate Fellowship from McGill University (2010), a Best Poster Presentation Award from the McGill University Health Centre (2014), and travel awards from the Division of Endocrinology and Metabolism (2011 & 2012), the Canadian Obesity Network (2010, 2012 & 2013), the Réseau de Recherche en Santé Cardiométabolique, Diabète et Obésité du Fonds de Recherche Santé jointly with the Institutes of Cardiometabolism and Nutrition (2014), the Canadian Public Health Agency of Canada (2012), and the Department of Epidemiology, Biostatistics and Occupational Health (2011 & 2012).

Financial support for *Manuscripts 2* and *5* **(Neighborhood walkability: Field validation of Geographic Information System Measures.** ***Am J Prev Med. 2013;*** **Jun;44(6):e51-52 and Neighbourhood walkability and daily steps in adults with type 2 diabetes. 2015.** ***PLoS One*****. In Press, doi: 10.1371/journal.pone.0151544)** was provided by an operating grant from CIHR (Principal Investigator: Kaberi Dasgupta, MOP-79275), a CIHR Catalyst Grant (Principal Investigators: Nancy A. Ross and Kaberi Dasgupta, 94431), and a grant from the Heart and Stroke Foundation of Canada (Principal Investigator: Kaberi Dasgupta: G-12-000251). Financial support for *Manuscript 6* **(Neighbourhood walkability and neighbourhood-based physical activity: An observational study of adults with type 2 diabetes. 2015.** ***International Journal of Behavioral Nutrition and Physical Activity*****. Under review)** was provided by a CIHR Operating Grant (Principal Investigator: Kaberi Dasgupta, CT0147520) and a Heart and Stroke Foundation of Canada Grant-In Aid Award (Principal Investigator: Kaberi Dasgupta). I led the writing of the Heart and Stroke Foundation of Canada Grant-In Aid Award under the supervision of Dr. Kaberi Dasgupta. Financial support was not required for the delivery of *Manuscript 1* as secondary data sources were used for this analysis. No specific funding was obtained for *Manuscripts 3* and *4.* The analyses for *Manuscript 4* were, however, conducted at the Quebec Interuniversity Centre for Social Statistics (QICSS), which is part of the Canadian Research Data Centre Network (CRDCN) and the services and activities provided by the QICSS are made possible by the financial or in-kind support of the Social Sciences and Humanities Research Council (SSHRC), the Canadian Institutes of Health Research (CIHR), the Canada Foundation for Innovation (CFI), Statistics Canada, the Fonds de recherche du Québec – Société et culture (FRQSC) and the Quebec universities.

RESEARCH ETHICS

Ethics approval was not required for *Manuscript 1* as it was a systematic review. Approval for the collection of the data used in *Manuscripts 3* and *4* was obtained by the Health Canada Research Ethics Board. Additional ethics approval from McGill University was not required as these studies represented secondary data analyses. To access these data, however, permission had to be granted by the Social Sciences and Humanities Research Council of Canada (12-SSH-MCG-3081) and the analyses for *Manuscript 4* had to be conducted at the McGill-Concordia in the Quebec Interuniversity Centre for Social Statistics (QICSS), which is part of the Canadian Research Data Centre Network (CRDCN). The views expressed in these manuscripts are those of the authors and not necessarily those of the CRDCN or its partners.

Procedures were approved for *Manuscripts 2, 5* and *6* by McGill University's Faculty of Medicine Institutional Review Board and all participating institutions. Participants provided written informed consent. Written informed consent was recorded using a consent form and procedure that was approved by McGill University's Faculty of Medicine Institutional Review Board. The signed research ethics statements from McGill University's Faculty of Medicine Institutional Review Board and all participating institutions are retained by the supervisor (Dr. K. Dasgupta) in accordance with McGill's policies on research ethics.

LIST OF ABBREVIATIONS

BMI	Body mass index
CES-D	Center for Epidemiologic Studies-Depression Scale
CFI	Canada Foundation for Innovation
CHMS	Canadian Health Measures Survey
CIHR	Canadian Institutes of Health Research
CI	Confidence Interval
CMAs	Census Metropolitan Areas
CRDCN	Canadian Research Data Centre Network
CrI	Credible Interval
CVD	Cardiovascular Disease
EV	Eigenvalues
FRQSC	Fonds de recherche du Québec – Société et culture
GIS	Geographic Information System
GPS	Global Positioning System
LUM	Land use mix
MVPA	Moderate-to-vigorous intensity physical activity
OR	Odds Ratio
PA	Physical activity
PEDS	Pedestrian Environmental Data Scan
QICSS	Quebec Inter-University Center for Social Statistics
RR	Relative Risk

SMARTER	Step Monitoring to Improve Arterial Health
SSHRC	Social Sciences and Humanities Research Council
VeDBA	Vector of the Dynamic Body Acceleration

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

TABLE OF CONTENTS

Chapter 7. ***Manuscript 5*** **- Neighbourhood walkability and daily steps in adults with type 2 diabetes**

Chapter 8. ***Manuscript 6*** **-** Neighbourhood walkability and neighbourhood-based physical activity: An observational study of adults with type 2 diabetes

Appendices

CHAPTER ONE | Introduction

Prior to the 19th century, cities were typically built around town squares that contained all of the main services required for daily living (e.g., grocers, butcher shops, post offices, banks and churches).[1,2] Surrounding these town squares were highly interconnected side streets that allowed people to travel easily from place to place and into the downtown core.[1] The highly connected streets were characterized by intermingled commercial and residential spaces where people commonly lived above street level shops.[3,4] This facilitated access to a variety of destinations and helped contain cities within relatively small geographic areas that could be traversed by foot.[1,3,5] This 'walkable' design was critical as transportation services were limited.[6] Although these historical cities can be found primarily in Europe, examples also exist in North America (Figure 1.1).

Figure 1.1 Examples of pre-World War II cities built around a town square (left: Old Town Square in Prague, Czech Republic; right: Montreal Old Port; Images taken from *www.trekearth.com* and *www.localmontrealtours.com*)

The Industrial Revolution (1760-1840) brought with it the invention of the steam locomotive and streetcars.[7,8] These new modes of transport changed how people travelled and how cities were built. Rather than people building homes in close proximity to the downtown core, cities began to expand outward along railway and streetcar lines - leading to the development of the first suburbs.[3,5]

Rise in the sales and demand for personal automobiles in the early to mid-1900's further changed the face of how cities were built. By 1929, one in five Americans owned a car.[9] Immediately following World War II in 1945, sales of passenger cars in North America rose sharply.[5,10] This paired with the inauguration of the US Federal Highway Act in 1956 allowed people living in cities to explore the country.[3] Owning a car and a home outside of the city became the American dream (Figure 1.2)[3] and further prompted the redevelopment of cities around motorized transportation.[3-6,11] For example, to accommodate the growing demand for homes that were outside of the city while still being within reasonable driving distance to city cores where most jobs were held, roads and highways were built and neighbourhoods began to develop around the peripheries of cities. This lead to the phenomenon known today as "urban sprawl".[3,12] Urban sprawl has continued until today.[1] In Canada, the population of census metropolitan areas (CMAs) grew by 1.4% between July 1,

JIM'S going away tomorrow . . . and there will be long, lonely days before he comes back.

But that little home sketched there in the sand is a symbol of faith and hope and courage. It's a promise, too. A promise of gloriously happy days to come . . . when Victory is won.

Victory Homes of tomorrow will make up in part at least for all the sacrifices of today . . . *and that's our promise!*

They will have *better living built in* . . . electrical living with new comforts, new conveniences, new economies to make every day an adventure in happiness.

Plan for your Victory Home now . . . the one sure way is to buy War Bonds. Every Bond you buy is an investment in your future happiness and security . . . every dollar you put into Bonds helps bring *our* boys back sooner—*and safer*. Buy another Bond today.

* * *

The General Electric Consumers Institute at Bridgeport, Conn., is devoted to research on wartime home problems such as: Nutrition · Food Preparation · Food Preservation · Appliance Care · Appliance Repair · Laundering · Home Heating and Air Conditioning. Helpful booklets are available from your G-E Appliance Dealer, or General Electric Consumers Institute, Dept. LS-5.

APPLIANCE AND MERCHANDISE DEPARTMENT, BRIDGEPORT, CONN.

Figure 1.2 Post-World War II posters promoting suburban living and car ownership (Images taken from *www.statemuseumpa.org* and www. and *www.iamesper.net*)

2013 and June 30, 2014.[13] This is in contrast to a population growth rate of 0.4% in non-CMAs.[13]

Modern suburban neighbourhoods are homogenous, generally consisting of only residential homes (Figure 1.3). This homogeneity renders motorized transportation attractive for even minor trips (e.g., buying some milk) since retail services are not within walking distance. Modern suburban neighbourhoods are also characterized by low residential densities and long winding roads - designs that potentially make walking to places and to visit people less convenient.[4] Reasons for these modern designs are numerous. They satisfy the demand for suburban living and they may slow traffic by preventing straight-line paths across neighbourhoods.[4,14] They may also require less planning, fewer building costs (e.g., non-grid patterned street networks require fewer intersections) and less collaborative efforts between urban planners and local governments (e.g., increasing land use mix would require zoning approval).

Figure 1.3 A modern North American suburb (Douglas County, Colorado; Image taken from *www.airphotona.com*)

Suburban life brought middle-class citizens a newfound freedom in the post-war era. The modern suburban neighbourhood was praised by early American urban planners and supporters of the Garden City Movement, including Clarence Stein and Henry Wright.[4,15] Despite the advantages of this new way of life, car ownership and suburban living led to an increased reliance on motorized transport.[3] Prior to 1945 most people had to do everything on foot, by bike, or using public transport. After 1945, people began to rely on cars to do even the smallest errands.[5] With over 70 years of hindsight, researchers have noted that the growing reliance on cars since 1945 and the development of ‘unwalkable’ neighbourhoods has paralleled the rise in physical inactivity.[16] Not surprisingly, this has led people to attribute decreases in physical activity to car use and/or living in unwalkable neighbourhoods[17,18] and has prompted researchers to study the link between the design of residential neighbourhoods, physical activity, and health.

Research on the role of neighbourhood designs in human health did not get fully underway until the mid 1990’s. During the mid 1980’s health research was influenced largely by the social cognitive[19] and trans-theoretical models of health.[20,21] These models led researchers to focus on identifying the individual-level determinants of health and health behaviours.[22,23] Despite increased knowledge regarding the importance of individual-level factors,[22,24-26] efforts to increase physical activity through individual-level change were met with limited success.[22,23,27] In 1988, McLeroy and colleagues published a seminal piece in which they introduced the social-ecological model to the field of health promotion.[28] Unlike previous models, the social-ecological model posited that although individual-level factors (e.g., education) influence one’s propensity to engage in positive health behaviours (e.g., physical activity and exercise), the social and physical environments in which people live either promote or restrict the influences of these individual-level factors (Figure 1.4).[28,29]

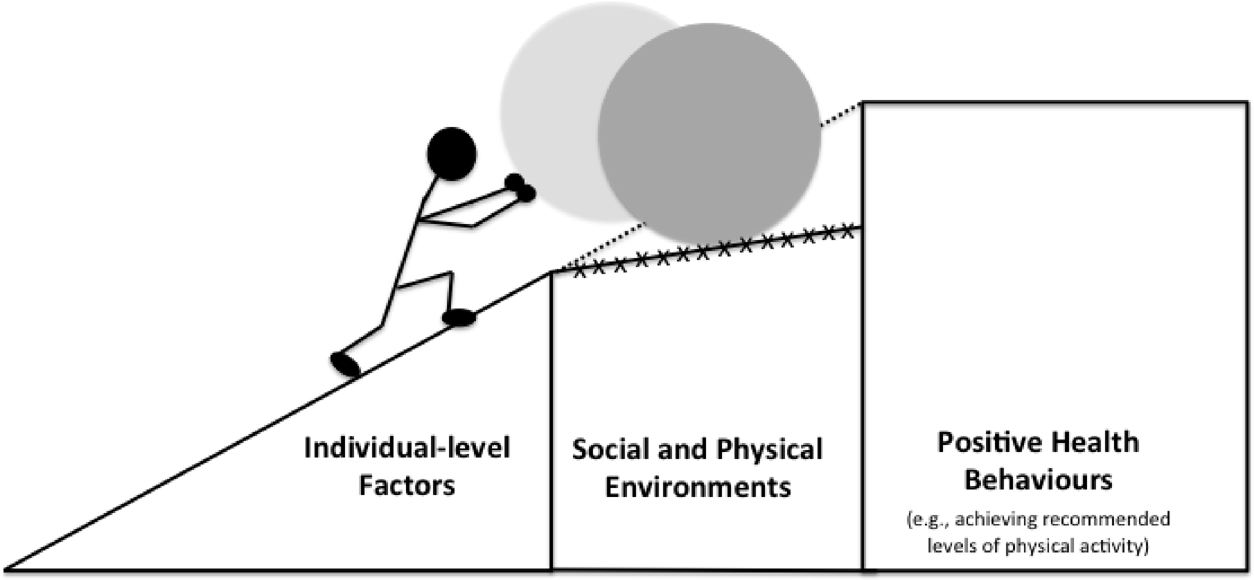


Figure 1.4 Socio-ecological model of positive health behaviours

In 1995, King and colleagues[30] published a review in which they advocated for the application of the socio-ecological model to the study of physical activity. In 1998, Sallis and colleagues[29] extended upon this review and proposed that in addition to the interpersonal, intrapersonal, institutional, community and public policy factors that are central to the socio-ecological model, consideration of the physical environments to which people are exposed is critical for understanding physical activity behaviour. They suggested that even though individuals must first become motivated to increase physical activity (i.e., an individual-level change), in the absence of choice-enabling environments (e.g., places to go), volitional attempts at increasing physical activity will be met with limited success. Following the publication of the paper by Sallis and colleagues in 1998,[29] there was a rise in the number of studies on the relationship between neighbourhood designs and physical activity.[31,32] Please see Appendix A for a summary of the major research initiatives that are currently underway. The study of neighbourhood designs is particularly appealing because neighbourhoods are amenable to change and intervening at the neighbourhood-level has the potential to impart benefits to large segments of the population.[29]

Since the late 1990's researchers have suggested that neighbourhood characteristics might be associated with higher levels of physical activity in adults. These include factors such as availability of walking paths, close proximity to community services, and neighbourhood aesthetics.[22,23,33,34] Researchers hypothesize that there are three large-scale features of neighbourhood designs that are correlated with higher levels of physical activity in adults. These include pedestrian-friendly **designs, diversity** of destinations, and population **density**.[35,36] The variables that best capture design, diversity and density are <u>street connectivity</u>, <u>land use mix</u> and <u>population and/or residential density</u>.[37,38] Although there are good conceptual reasons to believe that these three factors are associated with the walking behaviours of adults, as will be outlined in the Chapter 2, there has been a heavy reliance on self-reported measures of physical activity and on significance testing both of which have limited the quality of the quantitative evidence supporting this hypothesis.

Street connectivity, land use mix and density: Why might they matter?

<u>Street connectivity</u> is commonly measured as the number of intersections per square kilometre within a neighbourhood. A greater number of intersections is indicative of increased ease of movement between origins (e.g., residences) and destinations (e.g., shops and parks).[38,39] Neighbourhoods with high connectivity contain a greater number of interconnected streets allowing for greater ease of access from Point A to Point B (i.e., via more direct travel routes) (Figure 1.5, left image).[38,40]

Figure 1.5 High (left image) and low (right image) connectivity neighbourhoods (Images taken from *www.switchboard.nrdc.org; www.google.ca/maps* and *www.airphotona.com*)

In addition to providing a more direct path of travel to destinations, high street connectivity slows traffic as a result of multiple stopping sites and allows pedestrians to reach their destination via a variety of routes – potentially making non-motorized transport more appealing. This is in contrast to low connectivity neighbourhoods, typically characterized by few intersections (e.g., long streets to suburb blocks) and barriers to direct travel (e.g., cul de sacs) (Figure 1.5, right image).[38,40] Low street connectivity is typical of modern suburban neighbourhoods. To urban planners, street connectivity is an important indicator of neighbourhood design. A positive association between street connectivity and walking would provide urban planners with evidence that maximizing the ease of movement within neighbourhoods (e.g., by designing neighbourhoods with well-connected street networks and/or walking paths) would make a neighbourhood more walking friendly.

Land use mix is a measure of the evenness of the distribution of the land uses that are contained within a neighbourhood.[39,41] The more types of land uses that are contained within a neighbourhood, the more convenient it is for residents to walk to services supplied by these areas.[37,42] For example, in many Montreal neighbourhoods, apartments are located above street-level shops and in close proximity to churches, schools and other services. This makes walking to these destinations relatively easy (e.g., the Plateau-Mont-Royal, Figure 1.6). This is in contrast to newer suburban areas (e.g., Kirkland), in which neighbourhoods are devoted to single land uses (e.g., residential zoning). Wide separation between land uses in modern neighbourhoods makes motorized transportation to points of interest a near necessity (Figure 1.7).[43,44]

Figure 1.6 A neighbourhood with a high degree of 'mixing' between commercial (street-level) and residential (above-shop apartments) land uses. Given the close proximity of walkable destinations, non-motorized transport is encouraged. (Image taken from *www.montrealnitelifetours.com*)

Figure 1.7 Two neighbourhoods with low heterogeneity in land uses. The neighbourhood on the left is limited to residential land uses whereas the neighbourhood on the right is limited to commercial land uses. Travel from an individual's residence to the mall would necessitate motorized transport. (Images taken from *www.wikipedia.org and www.city-data.com; Left image is credited to IDuke, 2005, a neighbourhood in Markham, Ontario*)

Population and/or residential density are defined as the number of people and/or residences in a predefined geographic area.[3] Neighbourhoods with greater residential or population densities are generally more conducive to non-motorized transport as a result of there being more people to visit and a greater demand for accessible community services, such as shops and parks.[38] This is in contrast to neighbourhoods with lower residential densities (i.e., a modern suburb) where there are fewer people within walking distance and thus a greater propensity for residents to select motorized transportation in order to make contact with other individuals.[38] For urban planners, residential density provides a critical number of individuals that, due to a greater demand for accessible community services, encourages the development of more walkable destinations, such as shops and parks. A positive association between density and walking would provide support for increasing the number of dwellings per usable area of land space as a means of encouraging non-motorized transportation among residents.

Street connectivity, land use mix and density: How are they measured?

Street connectivity, land use mix and population/residential density can be assessed using either participant-reported or researcher-assessed measures.[2] Participant-reported measures (i.e., questionnaires, surveys, or interviews) capture people's perceptions regarding the walkability of the neighbourhoods in which they live. While these tools largely capture individuals' perceptions regarding social and micro-scale features of neighbourhoods (e.g., safety and aesthetics), questionnaires that assess residents' perceptions of large-scale features of neighbourhood designs, including street connectivity, land use mix and residential density have also been developed (e.g., Neighborhood Environment Walkability Survey[45]). Researcher-assessed methods are other ways of measuring neighbourhood walkability. Three commonly used researcher-assessed methods include neighbourhood audits, use of a Geographic Information System (GIS), and ready-to-use measures. Each of these methods are described here:

Neighbourhood Audits

Neighbourhood audits allow researchers to assess neighbourhood characteristics via direct observation. Many checklists have been developed for this purpose. As with the tools developed to assess people's perceptions of neighbourhood walkability, these checklists allow researchers to survey a wide variety of features of neighbourhood environments, including social and built environment characteristics (e.g., safety, attractiveness, number of land uses). Some examples include the Pedestrian Environment Data Scan,[46] the Microscale Audit of Pedestrian Streetscapes (MAPS),[47] and the Analytic Audit Tool and Checklist Audit Tool.[48]

While audits allow for detailed assessments of neighbourhoods by 'unbiased' observers, they have some limitations. Due to the significant amount of groundwork that is required to visit neighbourhoods, audits are impractical for studies with large sample sizes and geographically dispersed neighbourhoods. Further, assessing larger-scale features (e.g., street connectivity) is difficult since the individuals conducting the audits usually visit only a small proportion of the neighbourhood. To overcome these limitations, Google Street View is being increasingly used in place of in-field audits.[49-52] This free and publicly available software allows researchers to virtually walk through neighbourhoods and assess characteristics of the built environment from the comfort of their offices. Although it is arguably easier to assess large-scale features of neighbourhood environments (e.g., street connectivity) using Google Street View, it is still limited in terms of its ability to measure large-scale features of neighbourhoods in a standardized manner. For this purpose, GIS is advantageous.

GIS

GIS is a geographic tool used to assess many geographic and environmental factors, including neighbourhood characteristics. It overcomes the limitations of neighbourhood audits and constitutes a modern and powerful approach to environmental assessment. It was developed in Canada, driven by the country's need to manage vast amounts of spatial data across large land areas (e.g., topographic mapping and surveys of land resources).[53] Today, digital spatial information is arguably one of the most influential aspects of the Internet age. Linking digital information about the social and physical characteristics of countries, regions and neighbourhoods for the purposes of understanding human health continues to be one of the most common applications of GIS in research.[54,55] I demonstrated the power of GIS in a paper that I recently published in the *International Journal of Epidemiology (*Hajna et al., August 2015, Div.1-6; Appendix B) to commemorate the 160th anniversary of the publication of John Snow's seminal essay *On the Mode of Communication of Cholera (1855)*. In this paper I retrieved the South London data that were deleted in subsequent reprints of Snow's essay and presented a first-time mapping of these data in time and space.

GIS-derived measures of neighbourhood characteristics, including street connectivity, land use mix and residential/population density, are obtained by overlaying publicly available data files (e.g., street shape files) onto maps containing spatially referenced information (e.g., home addresses) (Figure 1.8[56]). The variables of interest (e.g., number of intersections) are then calculated within predefined geographic areas (e.g., residential neighbourhoods) using software that has been developed for this purpose (e.g., ArcMap 10.1, ESRI, Redlands, CA).[2]

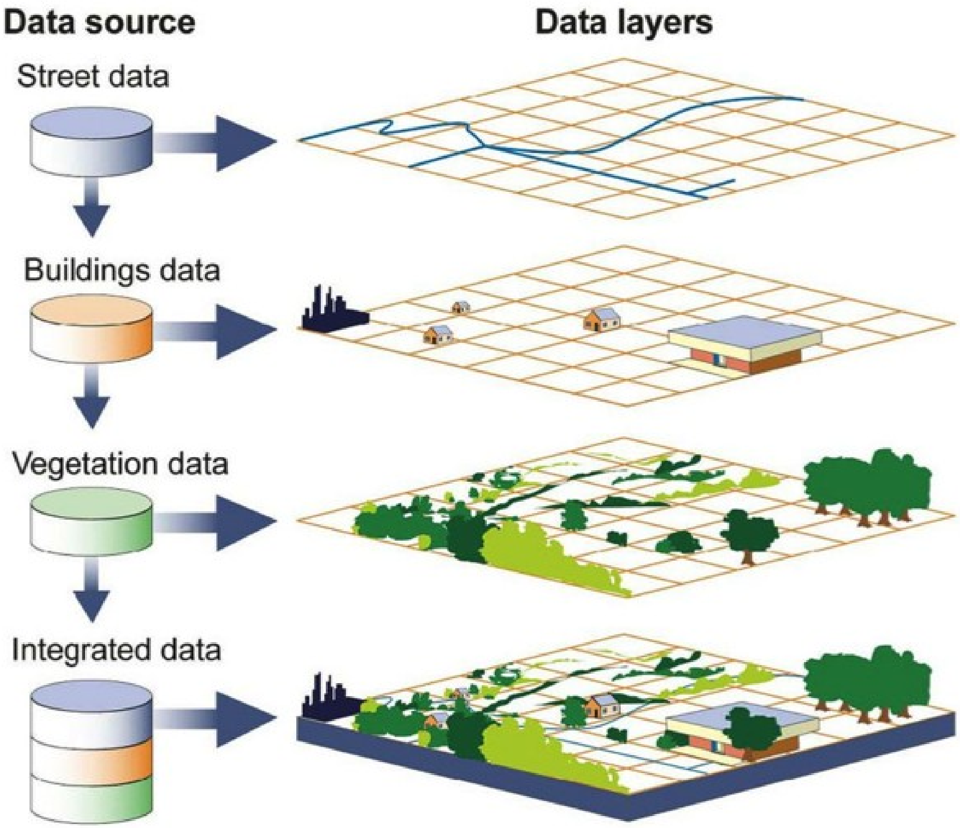


Figure 1.8 Simple representation of a Geographic Information System (Image taken from *www.nationalgeographic.com*)

Three types of buffers are commonly used to define residential neighbourhoods - the spatial units of analysis for deriving neighbourhood-based street connectivity, land use mix and population/residential density.[57] These include circular, line-based, and polygonal buffers. These buffers are typically drawn around a single spatial location, such as the centroid of a postal code address or a latitude/longitude coordinate. Circular buffers cover the entire area that is located within a predefined "as the crow flies" distance (e.g., 500-m) from a single spatial location (Figure 1.9, grey circle[57]). Line-based buffers are limited to areas covered by existing road networks and more closely represent the roads and immediate areas to which an individual is exposed (Figure 1.9, dark blue line[57]). Polygonal buffers are less restrictive than line-based buffers while still taking into account existing road networks and how they may restrict travel within the neighbourhood. They are derived by delineating a specific distance down every street leading from a single spatial location and connecting the vertices of these endpoints (Figure 1.9, red dotted line). The advantage of polygonal buffers is that they best approximate the environment that an individual is exposed to and may be the most sensitive for detecting associations between neighbourhood characteristics and walking.[58,59]

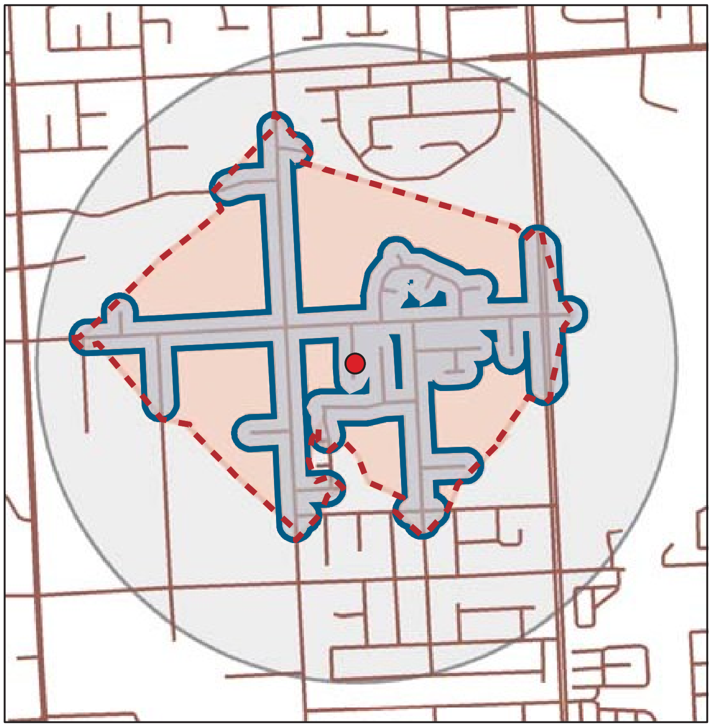


Figure 1.9 Comparison of three buffer shapes that may be used to delineate home neighbourhoods (Image taken and adapted from Oliver et al., 2007).

When GIS is used to derive street connectivity, land use mix and population/residential density, researchers often combine these variables into weighted or unweighted indices by summing the z-scores of these three measures.[39,41,60] The advantage of combining these variables into a single index is that it provides a measure of overall neighbourhood walkability. Since these variables are often correlated (i.e., areas with a greater population density typically have greater street connectivity and a greater land use mix) creating an overall walkability index also helps researchers avoid potential modeling problems related to collinearity.[39,41] (*Please note:* While I examined the independent associations of street connectivity, land use mix and population/residential density on walking/physical activity in all of my substantive studies (*Manuscript 4, 5,* and *6*), my primary exposure of interest was an unweighted GIS-derived neighbourhood walkability that represented the sum of z-score of these three variables. Weighting would have been appropriate had I had *a priori* evidence that one of these three variables were more strongly/differently associated with my outcomes of interest (i.e., walking/physical activity) or if I were creating a predictive model and I wanted to weight the variables based on their actual associations with my outcome of interest. Neither of these situations held, so my primary exposure of interest was an unweighted GIS-derived neighbourhood walkability index.)

Ready-to-use Measures

While GIS is a powerful tool for deriving measures of neighbourhood walkability and provides researchers with flexibility in how they derive these variables, this method requires expertise in spatial data analyses. To help researchers with limited expertise in these types of analyses, to facilitate comparability of measurement across studies, or just to help researchers save time, several ready-to-use measures of neighbourhood walkability and friendliness for active/public transport have been developed. Examples include the Transit Score®, the Bike Score®, and the Walk Score®. The Walk Score® is relevant to the construct of neighbourhood walkability and is being increasingly used in the study of how neighbourhood designs influence physical activity behaviours.[61-64] It is a validated measure of the walkability of a geographic location based on its proximity to 13 walkable destinations.[65-67] The Walk Score® can be readily derived by researchers using the publicly available interface (www.walkscore.com) and only requires users to enter the address (e.g., postal code, street address, or latitude/longitude) of the area that they wish to assess. The Walk Score® is calculated based on an algorithm that assigns equal weights to each walkable destination.[68] A higher Walk Score® is indicative of a higher diversity of services and higher population density which creates a higher demand for such services.[69] The outputted score ranges from 0 to 100. Definitions of neighbourhood walkability have been assigned based on this score as follows: 'Car-Dependent' (Score: 0 to 24; A car is required for almost all errands), 'Car-Dependent' (Score: 25 to 49; A car is required for most errands), 'Somewhat Walkable' (Score: 50 to 69; Some errands can be done on foot), 'Very Walkable' (Score: 70-89; Most errands can be done on foot), and 'Walker's Paradise' (Score: 90 to 100; A car is not required for daily errands).[70] It should be noted that the Walk Score® that I used in my doctoral research was based only on proximity to walkable destinations. Since the completion of my doctoral manuscripts a new version of the Walk Score® has been released (i.e., the Street Smart Walk Score®). In addition to measuring proximity to walkable destinations, the Street Smart Walk Score® also incorporates intersection density, average block length, and land use mix, and accounts for walkable routes when calculating proximity to walkable destinations - providing an overall metric of neighbourhood walkability similar to what I have calculated using my GIS-derived neighbourhood walkability index.[71]

Street connectivity, land use mix and density in health: What does the literature say?

There is some evidence that rates of obesity,[72-74] insulin resistance,[75,76] and diabetes[73,77,78] are lower in neighbourhoods with more walking friendly characteristics (e.g., greater resources for physical activity). For example, in a recent analysis of 214,882 recent immigrants and 1,024,380 long-term residents (i.e., defined as having provincial healthcare coverage for >10 years) living in Toronto (Canada), it was found that less walkable neighbourhoods (based on population density, residential density, street connectivity, and the availability of retail stores and services) were associated with a higher incident diabetes.[77] After adjustment for age and area-level income, immigrant men who lived in the lowest compared to the highest quintile of walkability had a 58% (95% CI 1.42, 1.75) increased risk of diabetes over 5 years of follow up. Similarly, immigrant woman who lived in the lowest compared to the highest quintile of walkability had a 67% (95% CI 1.48, 1.88) increased risk of diabetes over 5 years of follow up. The same association, though slightly attenuated, was observed in long-term residents (i.e., relative risk (RR): 1.32, 95% CI 1.26, 1.38 in men; RR: 1.24, 95% CI 1.18, 1.31 in women). Similar findings were reported in a recent analysis of 512,061 adults living in Sweden. In this study adults living in the lowest decile of neighbourhood walkability (based on street connectivity, land use mix, and residential density) were found to have a 33% higher odds of developing diabetes over four years of follow-up (Odds ratio (OR): 1.33, 95% CI 1.13, 1.55). This association attenuated after adjustment for socio-demographic factors including age, gender, income and education (Adjusted OR: 1.16, 95% CI 1.00, 1.34).[78] **Walking is one of the presumed mediators of the relationships that have been observed between neighbourhood walkability and cardiometabolic health outcomes (Figure 1.10).**[72,73,77]

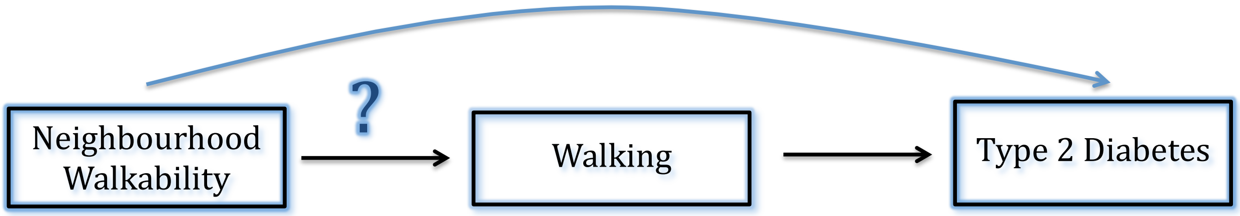


Figure 1.10 Presumed mediating role of walking in the associations that have been observed between neighbourhood walkability and cardiometabolic health outcomes, such as type 2 diabetes.

Neighbourhood walkability and walking: What we do and do not know

Walking may be divided into two categories: utilitarian walking and leisure-time walking.[79,80] Adults who live in higher density neighborhoods with many amenities and well-connected streets report higher levels of utilitarian walking (i.e., walking for a specific purpose like to go to work or school or for shopping).[81-83] In contrast, adults living in less walkable neighbourhoods (based on the Walk Score and street connectivity), have been found to report higher levels of leisure-time walking (e.g., going for an evening walk).[83,84] It has been suggested that since walkability is positively associated with utilitarian walking and negatively associated with leisure-time walking, the two may cancel each other out and result in no benefit to overall walking levels.[84] While some researchers have found evidence to support this hypothesis,[61,84] other studies have found positive associations between walkability and total walking.[83,85,86] Studies that use objective measures of both exposures and outcome are needed to elucidate the walkability-total walking relationship.

While the association of walkability with utilitarian walking and leisure-time walking is of interest, **total walking** is arguably the most salient outcome for cardiometabolic health. Higher total walking has been linked to improved markers of cardiometabolic health risk (e.g., lower body mass index and lower blood pressure) in general adult populations.[87-90] For example, in a recent analysis of 304 employed South African adults (37 ± 9 years), those who accumulated <5,000 steps/day had a higher average BMI than those who accumulated ≥10,000 steps/day (i.e., 28.1±7.1 kg/m^2 *versus* 26.1±3.6 kg/m^2).[88] Those who accumulated <5,000 steps/day compared to ≥10,000 steps/day also had a higher average waist circumference and higher systolic blood pressure (i.e., waist circumference: 89.9±15.3cm *versus* 83.0±8.6cm; systolic blood pressure: 122.2±15.5 *versus* 117.8±11.1; n=111).[88] These markers of cardiometabolic health are in turn associated with the risk of premature mortality.[91-94] In a meta-analysis of data from one million adults from 61 prospective studies, reductions in systolic blood pressure were associated with important reductions in risk of cardiovascular mortality across every decade of life (i.e., 40 to 89 years).[92]

While the benefits of higher total walking are clear in studies of general adult populations, the benefits of higher total walking may be particularly pronounced in adults with type 2 diabetes.[95] This is because adults with type 2 diabetes are highly inactive and already at a two-to four-fold risk of cardiovascular events and premature mortality compared to the general population.[96-100] In a 10-year prospective study of older US adults (50 to 90 years) with (n=347) and without type 2 diabetes (n=1,317), adults who self-reported walking for at least one mile (≅1.6 km) per day (compared to non-walkers) had a reduced risk of non-coronary heart disease mortality.[95] The observed associations were stronger in those with type 2 diabetes (HR: 0.19, 95% CI 0.04, 0.86) compared to those without type 2 diabetes (HR: 0.55, 95% CI 0.32, 0.96).[95] Among NAVIGATOR trial participants (i.e., adults with impaired glucose tolerance),[101] pedometer-assessed steps at baseline (HR for a 2,000 steps/day increment: 0.90, 95% CI 0.84, 0.96) and change in steps over an average follow-up of six years (HR per 2000 steps/day increase: 0.92, 95% CI 0.86, 0.99) led to reductions in cardiovascular disease events, (i.e., cardiovascular mortality, stroke, or myocardial infarction). In a study of over 2,896 US adults (18 to 95 years) with type 2 diabetes who participated in the National Health Interview Survey, self-reported walking three to four hours per week for exercise (compared to no walking) was associated with 54% (HR: 0.46, 95% CI 0.29, 0.71) and 53% (HR: 0.47, 95% CI 0.24, 0.91) reductions in all-cause and cardiovascular disease mortality, respectively, over eight years of follow-up.[102]

Measurement of Total Walking

Total walking can be assessed using self-reports or researcher-assessed methods. Self-reported measures of walking are often required for assessing walking behaviours in large cohorts where use of biosensors is not practical or when the goal is to discriminate between utilitarian and leisure-time walking. Many questionnaires have been developed for assessing walking in adults.[103] Some examples include the Past Year Total Physical Activity Questionnaire (PYTPAQ),[104] the Global Physical Activity Questionnaire (GPAQ),[105] and the Physical Activity for Adults Questionnaire (PAAQ).[106] A frequently used tool is the International Physical Activity Questionnaire (IPAQ). Two versions of the IPAQ exist: a short-form and a long-form. The short-form IPAQ is a 9-item questionnaire that queries the time that adults (18-65 years old) spend walking, in vigorous and moderate intensity activity, and in sedentary activities.[107] The long-form IPAQ is a 31-item questionnaire that queries physical activity behaviours within five domains, including household and gardening activities, work-related activities, active transport (e.g., biking), leisure-time physical activities, and sedentary activities. Both versions have been validated for use in adults based on data collected from 12 countries.[107] The short form has been recommended for population-based monitoring of physical activity and the long-form has been recommended for research purposes where more detailed information regarding physical activity behaviours may be needed.[107]

The disadvantage of self-reported measures of physical activity such as walking is that they are subject to recall and reporting bias[106,108-111] and may lead to the biased estimation of associations with health outcomes.[112] In a recent study by Lim and colleagues, it was demonstrated that use of self-reported physical activity levels (i.e., estimated using the GPAQ) attenuated the association between physical activity and prevalence of self-reported diabetes and obesity (based on self-reported height and weight).[112] To avoid the limitations of self-reported measures, when the necessary resources and expertise are available, biosensor-assessed measures of total walking are recommended. The step count functions of accelerometers and pedometers are commonly used for this purpose.[113-115] Accelerometers are small devices (approximately 20 grams) that are worn on the hip, wrist or ankle. These devices rely on components (e.g., piezoceramics) that convert mechanical energy (i.e., physical activity) into electrical signals.[116,117] Manufacturers of accelerometers have their own unique algorithms to convert these electrical signals into meaningful outcomes (e.g., minutes in moderate-vigorous intensity physical activity).[118-120] Many types of accelerometers exist. One that has been validated for use in adults and that is extensively used for research purposes is the ActiGraph.[119,121] Given the high cost of accelerometers (e.g., approximately $300 CAD based on 2015 prices for an ActiGraph wGT3X-BT monitor),[122] they are impractical for large population-based studies. For larger studies, pedometers are a more cost-effective choice, costing between $15 and 35 CAD.[115,123] Pedometers weigh approximately 20 grams and are worn on the hip. Traditional pedometers measure daily steps via software that counts the back-and-forth motion of a lead ball or pendulum that moves with the sway of the hip.[124] Newer models rely on microelectromechanical systems (e.g., piezoceramics), as those found in accelerometers, to count the number of steps that are taken.[124] As with accelerometers, many models of pedometers exist and have been shown to provide accurate assessments of total habitual walking in adults.[113,125,126]

In addition to providing accurate assessments of habitual levels of total walking in adults, accelerometer/pedometer daily steps are an appealing outcome for use in research as they are simple to understand. Easily interpretable cut-offs for daily steps have been proposed (Table 1.1) and the recommendation to achieve 10,000 steps per day is well publicized in the media making the concept of daily steps a familiar concept among the public.[115,127-130] This allows researchers to quantify the association between exposures (e.g., neighborhood walkability) and physical activity in a meaningful way.

Table 1.1 Activity level cut-offs proposed for daily steps (Tudor-Locke et al., 2008)

Category	Steps/day
Sedentary	<5,000
Low active	5,000 to 7,499
Somewhat active	7,500 to 9,999
Active	10,000 to 12,499
Highly active	≥12,500

Current Gaps in Knowledge

While there is some evidence that adults living in more walkable neighbourhoods (based on street connectivity, land use mix and population/residential density) may be associated with higher levels of total walking, there remain important gaps in the literature. These need to be addressed in order to fully elucidate the role that large-scale features of neighbourhoods designs have in the amount of total walking that people achieve:

1. <u>There is a need for studies that quantify the neighbourhood walkability-physical activity association using meaningful and interpretable estimates of association.</u> As will be outlined Chapter 2, the majority of studies that have been conducted to date have relied heavily on tests of statistical significance. Since tests of statistical significance provide no information regarding the magnitude of the observed effects and a statistically significant result (i.e., a p-value <0.05) may have no clinical importance, this approach has precluded our ability to draw conclusions regarding the magnitude and importance of the observed associations. Studies in which the size of the observed effects are quantified and interpreted in the context of the corresponding variance estimates are needed.

2. There is a need for more studies that use biosensor-assessed total walking as an outcome. Most studies on the walkability-total walking relationship have relied on self-reported measures of walking. Very few have examined this relationship using biosensor-assessed measures of total walking – measures that avoid biases associated with self-report and that allow for greater accuracy in the estimation of associations.

3. There is a need for more studies that adequately control for potential confounders of the walkability-physical activity relationship. Most of the studies that have been conducted to date have either not accounted for important potential confounders (e.g., car access, residential self-selection) or have done so using crude proxies that are subject to residual confounding (e.g., using neighbourhood-level rather than individual-level income). For a summary of the potential confounders/covariates of the neighbourhood walkability-physical activity relationship, please to Appendix C.

4. There is a need for studies on the association between neighbourhood walkability and biosensor-assessed daily steps in North America. All of the studies that have been conducted previously have been conducted in Europe and in Asia (Please see Chapter 3, *Manuscript 1*). Since physical activity levels are lower[131] and reliance on cars is greater[132] in North America than in Europe and in Asia and because there may be important cultural preferences surrounding car use and the role of neighbourhoods in daily living, the association between neighbourhood walkability and biosensor-assessed total walking may be different in the North American context.

5. There is a need for studies to quantify the walkability-biosensor assessed total walking relationship in chronic disease population, such as in adults living with type 2 diabetes. Given that adults with type 2 diabetes 1) are generally unmotivated to engage in regular physical activity,[133-135] and 2) prefer walking over any other form of physical activity,[136-141] the environment may have a particularly important role to play in either promoting or restricting the physical activity behaviours of this population.

Study Objectives

The objective of my doctoral work was **to estimate the association between GIS-derived neighbourhood walkability (based on street connectivity, land use mix and population/residential density) and biosensor-assessed total walking** in the general Canadian adult population and in adults with type 2 diabetes. The specific objectives of the six manuscripts that comprise my thesis are summarized below:

Manuscript 1: To summarize the current state of knowledge on the association between neighbourhood walkability (based on GIS-derived street connectivity, land use mix, and population and/or residential density) and biosensor-assessed daily steps in adults.

Manuscript 2: To validate the GIS-derived measures of neighbourhood walkability that I will be using in my substantive studies *(Manuscripts 4, 5 and 6),* by estimating their correlations (both individually and in a combined index) with neighbourhood walkability assessed using an in-field audit and a participant-reported questionnaire.

Manuscript 3: There is evidence that the entropy formula that is commonly used in the literature to calculate land use mix has been misspecified in previous studies. Before using this measure in my substantive studies (*Manuscripts 4, 5 and 6*), I quantified the amount of bias that would result from the misspecification of this entropy formula when estimating the association between land use mix and daily steps.

Manuscript 4: To estimate the association of GIS-derived neighbourhood walkability (based on street connectivity, land use mix, and population density) and the Walk Score® with accelerometer-assessed daily steps and participant-reported utilitarian walking in a large sample of Canadian adults who participated in Cycle 1 of the Canadian Health Measures Survey.

Manuscript 5: To estimate the association between neighbourhood walkability (participant-reported, in-field audits, GIS-derived, and the Walk Score®) and pedometer-assessed daily steps in a clinical sample of adults with type 2 diabetes.

Manuscript 6: To determine if increased precision in the match between exposures and outcomes improves the estimation of the walkability-total physical activity relationship. I did this by estimating the association of GIS-derived neighbourhood walkability (based on street connectivity, land use mix, and population density) with both neighbourhood-based and non-location specific physical activity in a clinical sample of adults with type 2 diabetes. In this study, I had to use total Vector of Dynamic Body acceleration as a proxy for total walking, since the algorithm used to convert activity counts into daily steps has not yet been validated. To make VeDBA conceptually more interpretable, however, I capitalized on pedometer data that was available in this study population. Specifically, I created a linear regression equation with which I was able to approximate the number of daily steps that would be associated with the observed change in VeDBA.

Summary

There is consistent evidence in the literature that adults that live in more walkable neighbourhoods (based on GIS-derived street connectivity, land use mix, and population/residential density) report higher levels of utilitarian walking, but whether higher neighbourhood walkability translates into higher levels of total walking remains unclear. The objective of my doctoral work was to elucidate this relationship in the Canadian context using objective measures of both exposures and outcomes. Understanding the link between neighbourhood walkability and total walking is an important step in informing the development of interventions that will help adults adopt more active lifestyles.

CHAPTER TWO | Literature Review

Since 2000 there have been many reviews published on the association between neighbourhood walkability and physical activity in adults. In this chapter, my objective is to provide an overview of the research that has been conducted by summarizing the findings of the key reviews that have been published between the years 2000 and 2015. I have organized my review into three periods: the *Early Years* (2000-2005), the *Middle Years* (2005-2010), and the *Recent Years* (2010 to 2015).

The neighbourhood walkability and physical activity literature is large. Neighbourhood factors that have been studied as potential determinants of physical activity include anything from social environments (e.g., perceived safety),[142-144] to small-scale features of built environments (e.g., availability of sidewalks and crosswalks and adequate lighting)[143,145] to large-scale features of neighbourhood environments (e.g., street connectivity).[41,146] I have restricted the focus of my literature review to the three large-scale features of neighbourhood environments that are central to the urban planning concept of 'walkability'. These include 1) street connectivity, 2) land use mix and 3) population/residential density. Since not all reviews explicitly use these three terms, I also included reviews that assessed neighbourhood measures that are directly related to one or more of these three large-scale features (e.g., accessibility to stores and services). Please note that a limitation of this body of research is that confidence intervals surrounding point estimates are rarely reported. When available I reported these in my literature review. If I did not report point and/or variance estimates, it may be assumed that the authors did not report these in their work.

The Early Years: 2000-2005

The first reviews of the neighbourhood walkability and physical activity literature began to appear in the early 2000's. In 2001, French and colleagues published a scoping review on the environmental influences on physical activity.[17] French and colleagues described Americans as "in love with their cars (pg. 322)" and noted that increased reliance on automobiles in North America paralleled reductions in physical activity. The authors drew on the work conducted by Cervero and Gorham in 1995 to demonstrate that transit-oriented neighbourhoods (defined as neighbourhoods built along a transit line or transit station, highly gridded, and built prior to 1945) generated 120% more walking or bicycle trips than automobile-oriented neighbourhoods (defined as neighbourhoods built in areas without transit lines, containing mostly random street patterns and built after 1945).[17,147] In 2002, Trost and colleagues conducted a similar scoping review in which they considered the correlates of higher levels of physical activity in adults. In their review, Trost and colleagues identified the study of the role environmental factors in physical activity behaviours as an emerging line of research.[148]

Until 2000 there were two separate groups of researchers who were studying the link between neighbourhoods and physical activity. These included health researchers and transportation researchers.[6,149] Health researchers focused on identifying the determinants of exercise (i.e., recreational/leisure-time physical activity), whereas transportation researchers sought to identify the predictors of utilitarian walking.[150-152] Between 2000 and 2005, four key reviews were published.[2,6,43,152] The aim of all four of these reviews was to highlight the potential of neighbourhood designs to help adults achieve higher levels of physical activity. Interestingly, this corresponded to a shift from health behaviour counselling to life-style based interventions for increasing physical activity that occurred during this time.[153-155] Three of the reviews published between 2000 and 2005 also had the specific goal of uniting the work of health and transportation researchers.[6,43,152] The specific findings of the four reviews are highlighted here:

Frank (2000)[6] drew on the work that was conducted in the late 1980's and early 1990's by authors in the transportation field. He gave some quantitative evidence to support the hypothesis that higher land use mix and higher population densities are associated with lower levels of automobile use. For example, in a study of neighbourhoods in San Francisco, Los Angeles, San Diego, and Sacramento, automobile ownership was 16% less in neighbourhoods with double the residential density.[156] In another study, employees in suburban centres in the greater Houston area were found to be 1.6 times more likely to leave their workplace for lunch using a car than employees working in downtown where there was greater access to restaurants and other services.[157,158]

Saelens and colleagues (2003)[43] conducted a review of 10 studies that had compared travel logs of people who were living in high versus low walkable neighbourhoods based on street connectivity, land use mix and residential density. Based on the results of these studies, the authors concluded that adults living in high versus low walkable neighbourhoods reported two more walking trips per week (i.e., 3.1 *versus* 1.4 trips). According to Saelens and colleagues, this translates to approximately 1 to 2 kilometers or 15 to 30 minutes of additional walking per week. Given earlier evidence that leisure-time walking did not appear to differ between adults living in high versus low walkable neighbourhoods,[159-161] the authors stated that the difference must be attributable to utilitarian walking.

Sallis and colleagues (2004)[152] summarized the neighbourhood and active transport literature that emerged from the transportation field but from a health perspective. They reiterated the finding by Saelens and colleagues (2003)[43] that adults living in high compared to low walkable walk approximately 15 to 30 more minutes per week and concluded that this is approximately equivalent to residents of high walkable neighbourhoods achieving the recommended levels of physical activity one extra day each week. Sallis and colleagues also stated that there appear to be two primary drivers of active transport (i.e., utilitarian walking/cycling): proximity to destinations (as captured by density and land use mix) and street connectivity (a reflection of how easy it is to access these destinations). The authors pointed out that despite consistent associations between neighbourhood designs and active transportation, the role of neighbourhoods on total physical activity had not been studied. They highlighted the need for more collaborative research between transportation and health researchers.

Badland and Schofield (2005)[2] noted that street connectivity, density and land use mix are all important predictors of transport-related physical activity (i.e., walking and cycling). Of these, they identified land use mix as the most important factor as it increases the convenience and accessibility of destinations. The authors also reiterated the previously reported findings that there is a 15 to 30 minute per week difference in self-reported walking between adults living in high and low walkable neighbourhoods[43,152] and they highlighted the need for comparable methods of exposure and outcome measurement across studies.

In addition to these large scoping reviews that were conducted between 2000 and 2005, five key systematic reviews were published. These are summarized here:

Humpel and colleagues (2002)[32] conducted a systematic review of all of the studies that had been published on the neighbourhood walkability-physical activity association in adults. Nineteen studies were identified. Ten of these examined the role of accessibility of facilities on physical activity levels in adults. Positive associations were reported between accessibility of facilities and higher self-reported physical activity in 4/10 studies. The authors did not report any effect estimates. They only reported if the observed association were positive, negative or null. Interestingly, not all four of these studies actually supported the conclusion of a positive association. For example, in the study by Sallis and colleagues (1997), there was no important correlation between self-reported convenience of facilities for physical activity and self-reported walking for exercise (R=0.09) and no association existed in multiple regression analyses after adjustment for neighbourhood socio-economic level ($p<0.68$, Adjusted $R^2=0$; no other data reported).[162]

McCormack and colleagues (2004)[163] identified 12 studies on the neighbourhood walkability-physical activity association in adults. Consistent positive associations were found between destinations (i.e., existence of accessible facilities) in a neighbourhood and higher levels of physical activity. The authors drew attention to the fact that there had been an overreliance in the literature on self-reported measures of neighbourhood walkability and that causality cannot be concluded based solely on observed correlations.

Owen and colleagues (2004)[80] were the first to conduct a systematic review of the studies that had focused on walking as an outcome. They were specifically interested in synthesizing what was known about the influence of neighbourhood environments on leisure-time walking, utilitarian walking and total walking. In their review, Owen and colleagues identified 18 relevant studies. They found that there was consistent evidence of a positive association between convenience of destinations and walking for specific purposes (utilitarian, recreation or exercise). The findings, however, were less consistent for total walking. The authors concluded that this area is a promising line of research with potential benefits to public health.

The review by Cunningham and Michael (2004)[164] was the first to synthesize the research that had been conducted on the neighbourhood walkability and physical activity association in seniors. Of the 27 articles that they identified on the association between neighbourhoods and physical activity, only 6 were relevant to seniors. In seniors, the authors found that safety and micro-scale features of neighbourhood environments (e.g., sidewalk conditions) were important, but having convenience and/or access to facilities were less consistently associated with their levels of physical activity.

The last systematic review to be conducted between 2000 and 2005, was conducted by Duncan and colleagues (2005).[165] This review included the first meta-analyses. The authors identified 16 studies that examined the associations between perceived neighbourhood characteristics and achieving sufficient levels of physical activity. After adjustment for age, income and education level, the authors demonstrated that people reporting access to physical activity facilities and access to stores and services in their neighbourhoods were more likely to engage in physical activity (OR: 1.20, 95% CI 1.06, 1.34 and OR: 1.30, 95% CI 1.14, 1.46, respectively).

Summary of Findings: The 2000-2005 Period

The first five years of the new millennium represented the birth of the neighbourhoods and physical activity literature. The key findings of this period were:

1) Street connectivity, land use mix and density appeared to be conceptually important components of what makes a neighbourhood 'walkable'.

2) There was preliminary evidence that street connectivity, land use mix, and density was associated with higher levels of utilitarian walking. Of these, land use mix appeared to be the most consistent correlate of utilitarian walking.

3) The associations were less consistent for leisure-time and total physical activity.

Perhaps more important than these findings were the contributions that this period made in terms of identifying the limitations of past studies and making recommendations for future research. Four key limitations and corresponding recommendations that were highlighted during this period included the following:

1) Most previous studies relied on self-reported measures of neighbourhood walkability and physical activity. Greater reliance on objective measures is needed.[2,163] GIS was identified as an important and emerging tool to be employed in future studies.[32,43]

2) Very few studies controlled for confounding in the neighbourhood walkability-physical activity relationship and very few considered the role of other predictors of physical activity. More consideration of confounders and covariates is needed.[43]

3) Exposure and outcomes were not consistently measures across studies. This precluded the pooling of results and made the drawing of comparisons across studies difficult. Standardized measures of neighbourhood walkability and physical activity are needed.[2,43]

4) The majority of studies were cross-sectional, precluding conclusions regarding causality.[148] More studies that assess physical activity behaviours before and after people move, and more pre/post neighbourhood intervention studies are needed.[166]

The Middle Years: 2005-2010

The largest contributions to the field during the 2005-2010 period were methodological. This period saw a great advancement in the development of participant-reported questionnaires,[167] audits tools,[168-170] and GIS methods.[171,172] Additional advances that were made included improved control for confounding and the concurrent consideration of other individual and socio-demographic factors that may be associated with physical activity. There were seven main reviews published between 2005 and 2010. Three of these were reviews of reviews. The key findings of these seven reviews are summarized here:

Heath and colleagues (2006)[173] summarized the findings of 12 studies in which the effectiveness of community-scale urban design and land use policy interventions on increasing levels of walking/biking were reported. No pooled estimates could be reported due to heterogeneity in the outcome measures, but the authors concluded that mixing land uses and improving connectivity are helpful strategies for increasing levels of physical activity. It is important to note that in this study, the authors used the term "intervention" incorrectly. The authors stated that "the preponderance of the evidence suggests that this type of intervention is associated with higher levels of physical activity (pg., S60)". The problem is that not all of the studies that they reviewed were interventions. The majority of the studies were cross-sectional and compared the physical activity behaviours of people living in neighbourhoods with differing degrees of walkability. By referring to the exposures as "interventions", Heath and colleagues gave the impression that these studies were quasi-experimental and/or pre-post interventions and thereby unduly overestimated the strength of the evidence base.

Gebel and colleagues (2007)[174] appraised the methodological characteristics and quality of the reviews that had been conducted between 2000 and 2005. The authors found that only 7 out of the 11 reviews correctly reported all of the results of the original studies. With one exception, whenever incorrect reporting occurred, non-significant associations were reported as significant – leading to what the authors refer to as "positive bias". The authors advocated for greater standardization in review methods and for users of data published in reviews (e.g., policy makers) to carefully critique the evidence base before making decision regarding policy change.

Bauman and Bull (2007)[175] conducted a review of 13 previously published reviews that summarized the literature on the environmental correlates of walking and physical activity. The most consistent correlates of self-reported walking and physical activity were proximity and accessibility to walkable destinations, high land use mix, high residential density and high aggregated score of neighbourhood walkability. The authors highlighted the need for greater standardization of measures across studies. They concluded that while there is evidence of some associations between neighbourhood walkability and physical activity, environmental changes alone might not be sufficient to increases physical activity. Social and individual-level factors will need to be leveraged as well.

Saelens and Handy's (2008)[149] review was the second to focus exclusively on walking as an outcome. The authors reviewed 13 reviews and 29 original research articles on the relationship of neighbourhood environments with leisure-time and utilitarian walking. The authors found that utilitarian walking was consistently associated with density, land use mix, and distance to non-residential destinations. The findings were less clear for leisure-time walking. This was among the first reviews to highlight the need for spatial matching between the built environment and physical activity. Another review that focused exclusively on the need for increased specificity in the estimation of the associations between environments and physical activity was conducted by Giles-Corti and colleagues in 2005.[176] The association between neighbourhood walkability and neighbourhood-based walking (e.g., how much walking done inside only inside of the neighbourhood) was examined in some previous studies,[177,178] but the majority of studies used non-location-specific measures of physical activity (e.g., total physical activity that is accumulated anywhere). This is a problem because estimating the link of neighbourhood walkability with physical activity that does not necessarily occur in the neighbourhood may underestimate the true association.[179] This review was also among the first to identify residential self-selection as an important potential confounder of the neighbourhood-walking relationship that needs to be addressed in future studies. Residential self-selection refers to the fact that people who have a preference for walking and active lifestyles may choose to move to more walkable neighbourhoods.[40,180-182] Without controlling for this, how much of the neighbourhood walkability-physical activity association is attributable solely to the neighbourhood compared to individuals' preferences for physical activity is unclear.[40]

The objectives of the review conducted by Cao and colleagues (2008)[166] were two-fold. The first was to summarize the methods that have been used in previous studies to assess and adjust for residential self-selection. The second was to review the studies (n=38) in which residential self-selection was considered in the analyses and to determine if adjusting for this factor would eliminate observed associations between neighbourhood characteristics and travel behaviours. The authors found that a statistically significant influence of the neighbourhood environment on travel behaviour was observed in all of the studies, even after controlling for residential self-selection. Cao and colleagues note that authors just describe their results in terms of significance. This is a problem as significance does not necessarily equal clinical or public health importance (i.e., a p-value of <0.05 may not be clinically important) and so the literature still gives no indication of how much neighbourhood environments actually matter. Cao and colleagues hypothesized that the reason why previous authors tend to only report the significance of the observed associations is that these associations are likely quite small. This, however, is, as they claim, not something that needs to be masked. Rather, it just supports the socio-ecological model of physical activity that postulates that there is a wide spectrum of factors that influence physical activity.

Brownson and colleagues (2009)[171] were the first to summarize the tools and metrics that had been used up until then to assess neighbourhood environments. These measures included in-field audits (20 tools were reviewed), participant-reported surveys (19 questionnaires were evaluated), and GIS-derived measures (50 studies were reviewed). The authors demonstrated that significant progress has been made in the development of neighbourhood measurement in the previous ten years. The development of a wide range of environmental assessment methods, the authors claim, has triggered rapid advancements in our understanding of the association between neighbourhood environments and physical activity.

Ewing and Cervero (2010)[40] reviewed 62 studies conducted on the association between the built environment and travel behaviour, including vehicle use and walking. This was an update of an earlier review that they had performed in which they only examined vehicle use as an outcome. In this updated review the authors found that self-reported walking was linked to land use mix, street connectivity (operationalized as intersection density), and the number of destinations within walking distance. However, using the economic measure of elasticity, the authors found that the independent associations between the environmental variables and walking were small (i.e., elasticity: 0.07, 0.15 and 0.39 for population density, land use mix and intersection density, respectively). Elasticity represents the ratio of the percentage change in one variable versus the percent change in another variable.[40] For example, in this study, a 1% increase in housing/population density was associated with a 0.15% increased probability of walking versus not walking. No confidence intervals around these point estimates were reported. The authors hypothesized that while the individual effects of these environmental factors are small, the cumulative effect of several environmental factors could be important.

Summary of Findings: The 2005-2010 Period

The research that was conducted between 2005 and 2010 confirmed the conclusion of the previous period that higher street connectivity, land use mix, and population/residential density appear to be, at least statistically, associated with higher levels of utilitarian walking. The evidence for leisure-time walking was less clear. Out of these three features, land use mix - most commonly defined as the ease of access or proximity to walkable destinations - was the most consistent correlate of higher levels of self-reported walking.

During this period, researchers recognized residential self-selection as an important confounder of the neighbourhood walkability-physical activity relationship. This led to an increase in the number of studies that accounted for residential self-selection.[166,183,184] Even when accounting for residential self-selection, there was evidence of associations between neighbourhood designs and travel behaviour (i.e., walking, biking, car use) in adults.[166] Researchers also made great strides forward in improving the measurement of neighborhood environments.[171] Both participant and researcher assessed tools were developed and GIS became a popular method for 'objectively' analyzing neighbourhoods.[41,69,171] In response to the concerns raised by authors regarding the lack of comparability across measure of neighbourhood walkability, the International Physical Activity and the Environment Network (IPEN) was developed.[185] The IPEN is a large international initiative that coordinated studies on the association between neighbourhood environments and physical activity in 12 countries.[186] An advantage of IPEN is that it allows for the pooling of results from multiple countries through the use of comparable methods of exposure and outcome assessments. In IPEN, neighbourhood walkability has been assessed using the Neighbourhood Environment Walkability Scale

(NEWS[167]) and GIS-derived neighbourhood walkability, and physical activity has been assessed using the International Physical Activity Questionnaire (IPAQ[107]) and accelerometers.[146,186]

There were two major limitations of the research that was conducted between 2005 and 2010. There was still a heavy reliance on participant-reported measures of physical activity. More studies in which researchers investigated the link between 'objective' assessments of both neighbourhoods and physical activity were needed. The second, arguably more important limitation was that, apart from reporting that there were statistically important effects, very few studies reported the magnitude of observed effects. Since statistical significance does not equal clinical or public health importance (i.e., a statistically significant result with a p-value of less than 0.05 may have no clinical importance),[187-189] it remained unclear if walkability was importantly linked to total walking.

Recent Years: 2010 to 2015

The year 2010 marked a new era for the field of neighbourhood walkability and physical activity research. There was a shift away from a heavy reliance on self-reported measures of physical activity to the use of more objective measures (e.g., accelerometer assessed MVPA and daily steps).[146,190-192] During the 2010 to 2015 period, there was also a new interest in examining the mediating and moderating roles of the neighbourhood-physical activity relationship[193] (e.g., car ownership,[194] cognitive factors,[195] socioeconomic status[196,197]). The contributions of this era are summarized in seven key reviews that were published during this time. The authors of these reviews were much more thorough in reporting their methods and results compared to the authors who published reviews in the previous five-year period. This, perhaps, came as a result of the critique of reviews that Gebel and colleagues published in 2007.[174] The findings of the seven key reviews published between 2010 and 2014 are presented here:

<u>Van Cauwenberg and colleagues (2011)[193]</u> published the first comprehensive review of studies on the association between neighbourhood environments and physical activity in older adults (≥65 years). The outcomes of interest included total physical activity, leisure-time physical activity, total walking and cycling, leisure-time walking and utilitarian walking. Thirty-one studies were identified. Participant-reported measures of neighbourhood characteristics were used in 13 studies, objective measures of neighbourhood characteristics were used in 12 studies and both participant-reported and researcher-assessed measures were used in 6 studies. No important associations were observed for overall walkability, street connectivity, land use mix or residential density with total physical activity. Results for the other outcomes were mixed.

<u>McCormack and Shiell (2011)[198]</u> summarized the neighbourhood walkability-physical activity literature based on study design. Specifically, they sought to compare the results of the cross-sectional (n=20) and the quasi-experimental studies (n=13). The authors concluded that preponderance of evidence suggests that street connectivity, land use mix, and population density are positively associated with utilitarian walking even after controlling for residential self-selection. Findings were less clear for leisure-time walking or other types of physical activity. When comparing cross-sectional study designs with pre-post studies based on either residential relocation or environmental modification), the authors found that pre-post studies provide less support for positive associations, with some even demonstrating null or counterintuitive results. While this conclusion is justified (based on a review of the original quasi-experimental studies

that they referenced), there are two important points to note. First, the counterintuitive findings generally referred to environmental interventions that were not directly related to street connectivity, land use mix or population/residential density. For example, the effect of a park improvement intervention[199] or the design of a new multi-use trail on physical activity[200] was assessed. The role of these factors may be different than the larger-scale features that I was interested in studying in my doctoral work. Second, McCormack and Shiell's analysis serves as a perfect example of why researchers need to interpret the work of others with caution. Referring to the pre-post study conducted by Wells and Yang (2008) on 32 woman living in the southeastern United States,[201] McCormack and Shiell state that the authors "found women who had moved to a neighborhood with fewer cul-de-sacs walked less than they had before, suggesting a negative association between connectivity and physical activity." In the original article by Wells and Yang, however, the authors state that "moving to an area with fewer cul-de-sac was associated with about 5,303 more steps per week (757 more steps per day)".

Durand and colleagues (2011)[202] reviewed 44 studies that had been conducted on the association between five neighbourhood characteristics that they referred to as "smart growth factors" on physical activity. These included diverse housing types, land use mix, residential density, compact development patterns, and levels of open space. This was the first review to provide evidence that the number of studies in which objective measures of neighbourhood walkability were used may have exceeded the number of studies in which participant-reported measures of neighbourhood walkability were used (45% of the reviewed articles used GIS-derived measures, 25% used participant-reported measures and 30% used both GIS-derived and participant-reported). No important effects of mixed land uses and compact building designs (a proxy for density) on physical activity were observed for 87% and 88% of the reviewed studies, respectively. In the discussion the authors state that “few studies reported significant associations between smart growth principles and physical activity or body mass (pg. 7)” Interestingly, however, their conclusions did not match their results. In their abstract the authors state that “Five smart growth factors (diverse housing types, mixed land use, housing density, compact development patterns, and levels of open space) were associated with increased levels of physical activity and walking (pg. 1)”. Similarly, in the conclusion of the main manuscript the authors state “the findings from this review suggest that smart growth planning principles hold promise for promoting physical activity, especially walking. (pg. 10)” This is an example of positive bias that Gebel and colleagues warned about in the review that they published in 2007.[174]

Ferdinand and colleagues (2012)[203] conducted a review on 169 articles that had examined the association between features of the built environment and physical activity. The authors found that 89.2% of articles reported a positive association and that studies that used researcher-assessed measures of physical activity (e.g., pedometers) were 18% less likely to find important effects compared to studies that used participant-reported measures. The authors highlight the need for more rigorous studies to determine if reconstructing built environments will lead to increases in physical activity.

Van Holle and colleagues (2012)[204] were the first to summarize the evidence that has emerged exclusively from Europe on the association between neighbourhood environments and physical activity studies in adults. They reviewed 70 articles and found that there was evidence of positive associations of street connectivity and land use mix on general active transport, but less consistent findings for total physical activity (self-reported and objective) and self-reported leisure-time physical activity.

The review published by Grasser and colleagues (2013)[205] was the first review to focus specifically on the studies that had been conducted using GIS-based measures of walkability (i.e., street connectivity, land use mix, density, and overall walkability). Based on their review of the 34 relevant articles that they identified, the authors found that higher population density, street connectivity and overall walkability indices were consistently associated with higher levels of utilitarian walking.

The review published by Moran and colleagues (2014)[206] represents the second systematic review of studies that were conducted on the neighbourhood environments-physical activity association in older adults (≥65 years). The first was conducted by some of the same authors in 2001. This 2014 review is different from the first in that the authors aimed to synthesize the literature based on the method that was used to assess the neighbourhoods (i.e., interviews *versus* direct observation). The authors identified and reviewed 31 studies. Access to facilities appeared to be the most consistent correlate of higher levels of physical activity when the assessment of neighbourhoods was based on both interviews and on direct observation. The authors recommended that mixed method approaches should be employed in future studies of neighbourhood environments and physical activity behaviours in adults.

Summary of Findings: The 2010-2015 Period

This period saw a rise in the use of biosensors to assess physical.[146,190-192] Beneficial associations of neighbourhood walkability on physical activity were less likely to be found when researchers assessed physical activity using biosensors.[203] Overall, the reviews that were conducted during the 2010-2015 period confirmed the findings from the previous five-year period that higher street connectivity, land use mix and residential density appear to be associated with higher levels of utilitarian walking in adults and that the evidence is less consistent for leisure-time and total physical activity.[61,84,193,198,204,207]

In 2008, Saelens and Handy's[149] drew attention to the need for spatial matching when examining the association between neighbourhood walkability and physical activity. It was not until the 2010-2015 period, however, given advances in GIS and GPS technologies,[208] that researchers were able to start more thoroughly addressing this issue. [209,210] This line of inquiry is still in its infancy, but based on the number of studies that have emerged in the last couple of years using real-time monitoring technology to assess physical activity behaviours and spaces in children and adults,[211-214] this will likely be a major line of research in the future.

The main limitation of the research conducted between 2010 and 2015 (as was the case with the research that was conducted during the 2005-2010 period) was that researchers continued to rely heavily on tests of statistical significance rather than quantifying the sizes of the observed effects and interpreting them in the context of the corresponding variance estimates. This has greatly limited our ability to draw conclusions regarding the magnitude of the observed associations and is a key limitation that I sought to address in my doctoral work.

Summary of the last 15 years of research

The body of evidence that has been published since 2000 suggests that there is a positive association between neighbourhood walkability (based on street connectivity, land use mix, and population/residential density) and self-reported utilitarian walking. The association with leisure-time and total walking is less clear. If neighbourhood walkability does influence physical activity, researchers have suggested that this effect is small.[40,166] Based on my review of the literature, however, conclusions regarding the effect size cannot be made as very few studies have adequately quantified these effects. To determine if altering neighbourhood environments has the potential to lead to clinically meaningful changes in total walking, studies are needed that 1) use objective measures of both neighbourhood walkability and total walking and that 2) quantify the observed effects using meaningful effect and variance estimates. In my doctoral research, I was specifically interested in elucidating the neighbourhood walkability-total walking relationship, as walking is the preferred form of physical activity among adults[137,215-217] and total walking (in comparison to utilitarian or leisure-time walking on their own) is arguably the most salient outcome for improved cardiometabolic health.

CHAPTER THREE | Manuscript 1

Associations between neighborhood walkability and daily steps in adults: A systematic review and meta-analysis

Samantha Hajna,[1] Nancy A. Ross,[1,3] Anne-Sophie Brazeau,[2] Lawrence Joseph,[1,2] Kaberi Dasgupta,[1,2]

BMC Public Health, 2015; 15:768

[1] Department of Epidemiology, Biostatistics and Occupational Health,
McGill University, 1020 Pine Avenue West, Montreal, QC, Canada.

[2] Department of Medicine, Division of Clinical Epidemiology,
McGill University Health Centre, 687 Pine Avenue West, Montreal, QC, Canada.

[3] Department of Geography, McGill University,
805 Sherbrooke Street West, Montreal, QC, Canada.

PREAMBLE

As I described in Chapter 2, there is evidence that higher neighbourhood walkability (based on street connectivity, land use mix, and population/residential density) is associated with higher levels of self-reported utilitarian walking. The association of neighbourhood walkability with total walking is less clear. The objectives of my first study (*Manuscript 1*) were two-fold. The first was to conduct a systematic review of the studies that have been conducted on the association between neighbourhood walkability (based on GIS-derived measures of street connectivity, land use mix, and population/residential density) and total walking (as measured by the step count function of accelerometers or pedometers) in adults. One of the main limitations of the research that has been performed to date has been has been a heavy reliance on statistical significance with limited reporting of parameter and variance estimates. This prevents us from drawing conclusions regarding the magnitude and clinical relevance of the observed associations. To address this limitation, the second objective of my first study was to quantify the relationship between neighbourhood walkability and total walking through a meta-analysis. This study has been published in *BMC Public Health* **(Hajna et al., 2015; 15:768**).

Hajna *et al. BMC Public Health* (2015) 15:768
DOI 10.1186/s12889-015-2082-x

BMC Public Health

RESEARCH ARTICLE **Open Access**

Associations between neighbourhood walkability and daily steps in adults: a systematic review and meta-analysis

Samantha Hajna[1], Nancy A. Ross[1,2], Anne-Sophie Brazeau[3], Patrick Bélisle[3], Lawrence Joseph[1,3] and Kaberi Dasgupta[1,3*]

Abstract

Background: Higher street connectivity, land use mix and residential density (collectively referred to as neighbourhood walkability) have been linked to higher levels of walking. The objective of our study was to summarize the current body of knowledge on the association between neighbourhood walkability and biosensor-assessed daily steps in adults.

Methods: We conducted a systematic search of PubMed, SCOPUS, and Embase (Ovid) for articles published prior to May 2014 on the association between walkability (based on Geographic Information Systems-derived street connectivity, land use mix, and/or residential density) and daily steps (pedometer or accelerometer-assessed) in adults. The mean differences in daily steps between adults living in high versus low walkable neighbourhoods were pooled across studies using a Bayesian hierarchical model.

Results: The search strategy yielded 8,744 unique abstracts. Thirty of these underwent full article review of which six met the inclusion criteria. Four of these studies were conducted in Europe and two were conducted in Asia. A meta-analysis of four of these six studies indicates that participants living in high compared to low walkable neighbourhoods accumulate 766 more steps per day (95 % credible interval 250, 1271). This accounts for approximately 8 % of recommended daily steps.

Conclusions: The results of European and Asian studies support the hypothesis that higher neighbourhood walkability is associated with higher levels of biosensor-assessed walking in adults. More studies on this association are needed in North America.

Keywords: Neighbourhood walkability, Daily step count, Walking, Environments, Physical activity

Background

Global rates of overweight and obesity are on the rise [1]. Although there have been small successes in the treatment and prevention of these conditions, no country has yet managed to reverse its epidemic [2]. This was highlighted in a series of six papers that were released in the February 2015 edition of the *Lancet* [2]. To more effectively combat the rising rates of obesity and obesity-related complications, interventions that acknowledge the interacting roles of individuals and their environments are needed [1–3]. Since the late 1990′s there has been growing interest in the role of neighbourhood environments on obesogenic behaviour [4–7]. The hypothesis is that the adoption of positive health behaviours will only be possible given choice-enabling environments [4, 8]. For example, in neighbourhoods with higher densities of fast food outlets, residents are more likely to consume fast food products than residents living in neighbourhoods where these outlets are not as prominent [9, 10]. One area of growing interest is on the role of neighbourhood designs on physical activity behaviour.

Street connectivity, land use mix and residential density are three large-scale features of neighbourhood

---

* Correspondence: kaberi.dasgupta@mcgill.ca
[1]Department of Epidemiology, Biostatistics and Occupational Health, McGill University, 1020 Pine Avenue West, Montréal, QC, Canada
[3]Department of Medicine, Division of Clinical Epidemiology, McGill University Health Centre, 687 Pine Avenue West, Montréal, QC, Canada
Full list of author information is available at the end of the article

designs that are commonly studied for their associations with physical activity [11–14]. ***Street connectivity*** is defined as the number of three or more-way intersections per square kilometre within a neighbourhood buffer, where a greater number of intersections is indicative of increased ease of movement between origins (e.g., residences) and destinations (e.g., shops and parks) [12, 15]. Neighbourhoods with higher intersection densities are typically designed using finer grid patterns and thus provide more straight-line options for travelling between origins and destinations [15]. In addition to this, such neighbourhoods slow traffic as a result of multiple stopping sites and allow pedestrians to reach their destinations via a variety of routes, making non-motorized transport more appealing [13]. ***Land use mix*** is a measure of the number of different types of land uses in a neighbourhood [12, 15]. Many downtown neighbourhoods have a large land use mix. Apartments are located above street-level shops and in close proximity to churches, schools and other services making it convenient for residents to walk to these locations [13]. This is in contrast to many newer suburban neighbourhoods where wide separation between residential and commercial land makes motorized transportation to points of interest a near necessity [15]. There are several ways to calculate land use mix [16]. The most common method is using the Shannon entropy score [13, 17]. The score ranges from 0 to 1 where a higher score is indicative of greater heterogeneity in land uses within a neighbourhood [12]. ***Residential density*** is defined as the number of residences per square kilometer of residential land area in the home buffer [14] or per square kilometer of the household's dissemination block [12]. Neighbourhoods with greater residential densities are generally more conducive to non-motorized transport as a result of there being more people to visit and a greater demand for accessible community services, such as shops and parks [15]. Street connectivity, land use mix and residential density are correlated [18]. As a result, when estimating their associations with health outcomes, researchers commonly aggregate these measures into an index that captures neighbourhood walkability – that is, the degree to which a neighbourhood is "walking friendly" [13, 18].

Higher neighbourhood walkability has been linked to higher levels of utilitarian walking (i.e., walking for specific purposes such as for travelling to school or to the grocery store) [19–22]. The findings are weaker or non-existent for leisure-time walking, suggesting that neighbourhood designs may not be important drivers of this type of physical activity [21, 22]. While utilitarian and leisure-time walking - two components of overall physical activity - are well studied, our understanding of the association of walkability with total walking is limited. Since total walking is arguably the more salient correlate of improved health outcomes [23–26], understanding its association with neighbourhood walkability is of particular interest.

Distinguishing between subtypes of physical activity (e.g., utilitarian and leisure-time walking), necessitates reliance on self-report. In contrast, total walking may be assessed using biosensors (i.e., pedometers or accelerometers). Daily steps as captured by biosensors provide a good estimate of total walking [27, 28]. Few studies, however, have examined the association between walkability and biosensor-assessed total walking [5]. The objective of the present study was to summarize the current body of knowledge on the association between neighbourhood walkability (based on street connectivity, land use mix, and/or residential density) and total walking (as captured by the daily step count function of biosensors) in adults.

Methods

Search strategy

The systematic review was conducted in compliance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [29]. A systematic search was conducted on titles, abstracts, keywords, MeSH terms and/or subject headings, as appropriate, that were ever indexed in PubMed, SCOPUS, or Embase (Ovid) prior to May 20, 2014 (i.e., from 1946 for PubMed, from 1996 for SCOPUS, and from 1996 for Embase (Ovid)). The following search string was used: [physical activity OR walk OR walking OR pedometer OR acceleromet* OR exercise OR actigraphy OR actimetry] *AND* [built environment OR walkable OR walkability OR street connectivity OR land use mix OR residential density OR population density OR environment planning OR neighborhood OR home environment OR urban design OR environment design OR residence characteristics OR Geographic Information Sys* OR geographic mapping]. The search strategy was developed by SH in consultation with a librarian from the Royal Victoria Hospital (Montreal, Quebec, Canada).

Article review and data extraction

All of the identified articles were compiled in Endnote (×4.0.2). Two independent reviewers (SH and AB) reviewed all of the titles and abstracts. The following inclusion criteria were applied: 1) study population ≥18 years, 2) the objective of the study was to estimate the associations between street connectivity, land use mix, and/or residential density (derived using Geographic Information Systems (GIS)) and pedometer or accelerometer-assessed daily steps, 3) effect estimates were reported, and 4) the article was published in English. Data were abstracted using a standardized form (SH). Abstracted information included study population, sample size, exposure and outcome measurement, and a summary of the reported effect estimates.

Statistical analysis

Confidence intervals (95 %) were not presented in the original papers and were calculated for the purposes of this analysis based on the reported information. Only the studies that reported differences in mean steps taken per day between high and low walkability neighbourhoods were included in the meta-analysis. The differences in means were pooled using a Bayesian normal-normal hierarchical model. At the first level of this model we assumed that the means within each group from each study followed normal densities, with study specific means [i, j], i = 1, 2, 3, 4 indexing the studies and j = 1,2 indexing the groups. We similarly assumed that the logarithms of standard deviations within each group from each study followed normal densities. At the second level of the hierarchical model, the study specific means within each of the two groups were again assumed to follow a normal density, with a global mean representing the overall mean within each group across studies, and a global variance parameter representing the spread of these means across the studies within each group. Similarly, the log standard deviations followed normal densities with the global mean representing the overall means of the log standard deviations, and the variance parameter indicating the spread of these values across studies within each group. We used normal (8000, 100,000) and uniform (0, 600) prior densities for the global means and log (SD), respectively. WinBUGS was used to run the hierarchical model (Version 1.4.3, MRC Biostatistics Unit, Cambridge UK). The forest plot was produced in R (CRAN, Version 3.0.1).

Results

Search results

The search that was conducted on articles published prior to May 20, 2014 yielded a total of 8,744 unique abstracts. After title and abstract review, a total of 30 articles were identified and underwent full article review. Of these, six met the inclusion criteria.

Qualitative analysis

Four of the six studies were conducted in Europe (Belgium [30, 31], Czech Republic [32], and Scotland [33]) and two of the six studies were conducted in Asia (China [34] and Japan [35]) (Table 1). All of the studies were cross-sectional. The measurement of daily steps and neighbourhood walkability was comparable across all studies. Daily steps were assessed using biosensors that have been validated for use in adults [36–42]. Neighbourhood walkability was assessed using comparable operational definitions of street connectivity, land use mix, and/or residential density. In three studies the authors predefined high and low walkable neighbourhoods and randomly selected participants from these areas [30, 31, 35]. In the remaining three studies [32–34], neighbourhood walkability was defined for each participant after they were selected into the study.

The point estimates of all six studies suggested that higher walkability was associated with a greater number of daily steps. Based on the confidence intervals, these associations were conclusive for only three of these studies [30, 32, 33]. In addition to examining the role of walkability with daily steps, three of the six studies assessed the role of walkability on utilitarian walking [30, 31, 35]. In the two studies from Belgium, adults living in high walkable neighbourhoods spent over 75 minutes more per week in utilitarian walking (76 minutes, 95 % CI 58 to 94 [31]; 82 minutes, 95 % CI 53 to 110 [30]) compared to people living in low walkable neighbourhoods. In the Japanese study, adults living in high walkable neighbourhoods reported walking 5 min per day less for utilitarian purposes than people living in low walkable neighbourhoods (95 % CI −10 to 1) [35].

Meta-analysis

The results of four studies could be pooled in a meta-analysis given that comparable effect measures were reported (i.e., the mean differences in steps/day between high and low walkability neighbourhoods) [30–32, 35]. The confidence intervals in the Belgian and Czech studies demonstrated clear positive associations of walkability with steps (Belgium [30]: 1222 steps per day, 95 % CI 131 to 2313; Czech Republic [32]: 2088 steps per day, 95 % CI 440 to 3736). Those in the Japanese study and the second Belgian study precluded definitive conclusions (Japan [35]: 1071 steps per day, 95 % CI −399 to 2540; Belgium [31]: 548 steps per day, 95 % CI −230 to 1326). A meta-analysis of these results demonstrated that participants living in high compared to low walkable neighbourhoods accumulated 766 more steps per day (95 % credible interval (CrI) 250 to 1271) (Fig. 1).

Discussion

Six studies have examined the association of GIS-derived street connectivity, land use mix, and/or residential density with pedometer or accelerometer-assessed daily steps in adults. Based on a meta-analysis of the results reported in four of these studies, living in high compared to low walkable neighbourhoods is associated with accumulating 766 more steps per day. This is on par with the seasonal deficits in daily steps that have been documented in the literature [25, 43, 44].

The majority of evidence in support of neighbourhood walkability as a correlate of higher levels of physical activity comes from studies that rely on self-

Table 1 Previous studies on the associations between GIS-derived walkability and daily steps in adults

						Overall Walking				Utilitarian Walking			
1st Author, Publication Date	N	Age	Location	Sampling Design	Neighbourhood Walkability Measurement (*cut-off for high vs. low walkability)*	Measurement	Findings	Association[a]	Difference in mean steps per day for people living in high versus low walkability neighbourhoods (95 % confidence interval) [b]	Measurement	Findings	Association[a]	Difference in mean time walking for utilitarian purposes for people living in high versus low walkability neighbourhoods (95 % confidence interval) [b]
Kondo, 2009	112	30 to 69	Hagi City, Japan	Sampling from high and low walkable neighbourhoods using a stratified random sampling method based on sex and 5-year age strata.	GIS-derived walkability based on street connectivity, residential density, land use mix *(not specified)*	Accelerometer	High walkability: 9364 steps/day; SE 567 Low walkability: 8294 steps per day; SE 491	INC	1071 steps/day (95 % CI −399 to 2540)	Min/day (IPAQ)[c]	High walkability: 3.3 min/day; SE = 2.1 Low walkability: 8.0 min/day; SE = 2.0	0	−5 min/day (95 % CI −10 to 1)
Van Dyck, 2011	350	42.4 ± 13.2	Flanders, Belgium	Sampling from high and low walkable neighbourhoods based on address list provided by the local government.	Urban *vs.* rural neighbourhoods based on GIS-derived walkability based on street connectivity and population density *(not specified)*	Pedometer	High walkability: 9323 steps/day; SD 3473 Low walkability: 8775 steps per day; SD 3942	INC	548 steps/day (95 % CI −230 to 1326)	Min/week (NPAQ)[c]	High walkability: 97.5 min/ week; SD = 96.4 Low walkability: 21.9 min/ week; SD = 72.3	+	76 min/week (95 % CI 58 to 94)
Dygryn, 2010	70	20 to 64	Olomouc, Czech Republic	Random selection of participants in city. Walkability was determined after inclusion into the study.	GIS-derived walkability based on street connectivity, residential density, floor area ratio, land use mix *(upper* versus *lower 5 deciles)*	Pedometer	High walkability: 11318 steps/day; SD 4091 Low walkability: 9230 steps per day; SD 2554	+	2088 steps/day (95 % CI 440 to 3736)	n/a	n/a	n/a	n/a
Van Dyck, 2009	120	20 to 65	Sint-Niklaas, Flanders (Belgium)	Sampling from high and low walkable neighbourhoods. Letters of invitation sent to randomly selected people. Letters were followed up with	Two neighbourhoods with greatest contrast in GIS-derived walkability based on street connectivity and residential	Pedometer	High walkability: 9318 steps/day, SD 3055 Low walkability: 8096 steps per day; SD 3044	+	1222 step/day (95 % CI 131 to 2313)	Min/week (NPAQ)[c]	High walkability: 104.33 min/ week; SD = 95.1 Low walkability: 22.83 min/	+	82 min/week (95 % CI 53 to 110)

Table 1 Previous studies on the associations between GIS-derived walkability and daily steps in adults *(Continued)*

				house visits to recruit people.	density (*not specified*)						week; SD = 61.0		
Robertson, 2012	76	27 to 66	Glasgow, Scotland	Sampling of people from Glasgow who were low active and part of low socioeconomic groups. Advertisement for participation was made in public locations (e.g., shops). Walkability was determined after inclusion into the study.	GIS-derived commercial and residential land use mix	Pedometer	A one-unit increase in land use mix (from no mix to a perfect mix) was associated with:			n/a	n/a	n/a	n/a
							1896 more steps/day (SE = 583) at *6-months* post community intervention	+	1896 steps/day (95 % CI 754 to 3038)				
							1260 more steps/day (SE = 622) at *12-months* post community intervention	+	1260 steps /day (95 % CI 40 to 2479)				
Zhang, 2014	1,100	46 to 80	Shanghai, China	Stratified random samples based on even distribution of community types. Selected households were sent letters of invitation. Walkability was determined after inclusion into the study.	GIS-derived street connectivity	Pedometer	Living in a neighbourhood one-SD above the mean street connectivity was associated with accumulating 21 more steps/day *(no variance estimates reported)*	Unknown based on reported information	Confidence intervals around the linear regression estimate could not be calculated based on the information reported in the text.	n/a	n/a	n/a	n/a

[a] Positive relationship (+); negative relationship (−); INC (inconclusive; more research is needed to better estimate this effect); 0 (no effect)

[b] 95 % confidence intervals were recalculated based on information reported in the original manuscripts (i.e., group sample sizes, standard deviations/standard errors, and/or p-values)

[c] International Physical Activity Questionnaire (IPAQ); Dutch Version of the Neighbourhood Physical Activity Questionnaire (NPAQ)

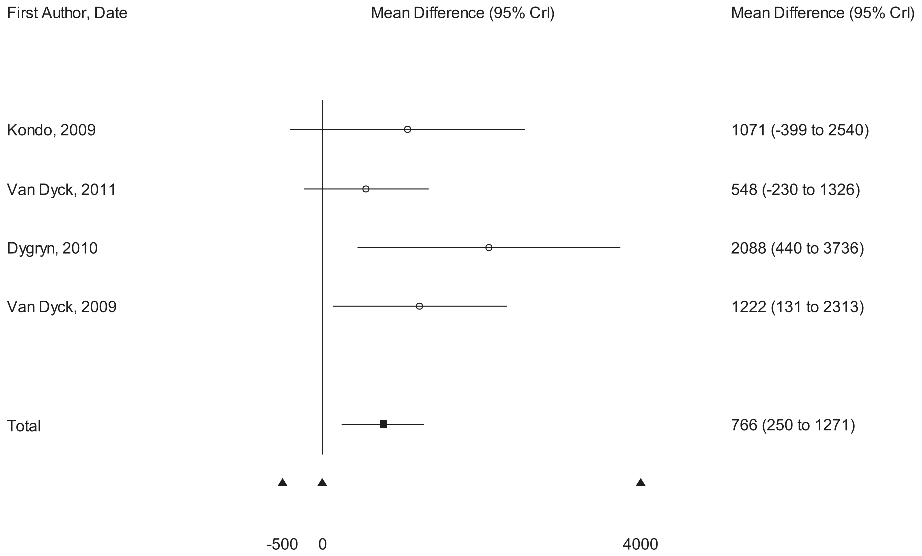


Fig. 1 *Short Title*: Forest plot of the results of previous studies on walkability and daily steps. *Detailed Legend*: Forest plot of the results of the previous studies that have been conducted on the association between Geographic Information Systems-derived measures of walkability (i.e., street connectivity, land use mix, and/or residential density) and pedometer and/or accelerometer-assessed steps per day in adults. The estimates represent the mean differences in daily steps between high and low walkability neighbourhoods (95 % credible intervals)

reported measures of physical activity [5, 45]. Recent reviews have summarized these findings, but other than suggesting that walkability is likely associated with higher levels of physical activity, these reviews do not quantify the association [5, 46–49]. Our study is the first to quantify the association between walkability and biosensor-assessed total walking in adults. All of the studies that were retained in the meta-analysis assessed steps using tools that have been validated for use in adults – thereby increasing the comparability of the outcomes across the studies. Daily step count as a measure of physical activity has several valuable properties. First, it is an accurate and easily understood measure of physical activity [27, 28]. Daily steps are more easily interpreted than accelerometer-assessed moderate-to-vigorous intensity physical activity [26]. Furthermore, there are established cut points for activity levels based on daily steps (i.e., sedentary: <5,000 steps/day, low active: 5,000 to 7,499 steps/day, somewhat active: 7,500 to 9,999 steps/day, active: 10,000 to 12,499 steps/day, highly active: ≥12,500 steps/day) [27] and pedometer-based step count interventions have been effective in facilitating increases in walking among adults [50, 51].

Some study limitations should also be noted. First, the pooled estimates are based on a relatively small number of studies. To build our understanding of the role of neighbourhood designs on walking in adults, more studies using comparable exposure and outcome measurements are needed. Second, although the operational definitions of street connectivity, land use mix and residential density were highly comparable across studies, some variability in measurement is expected due to between-country differences in actual walkability [14] and in the quality of the spatial data that were used to calculate walkability. However, the bias arising from this variability is offset given that we pooled relative (i.e., high compared to low walkable neighbourhoods) rather than absolute estimates of walkability (i.e., actual residential density). Third, we only estimated the associations between walkability and daily steps as defined by three large-scale features of neighbourhood designs (street connectivity, land use mix, residential density). Daily steps may be associated with other components of walkability, such as neighbourhood safety, presence of amenities, and social cohesion. Research on the associations of these features with daily steps is encouraged as a means of building our understanding of the role that environments have on the total levels of physical activity that adults achieve.

Conclusions

Our analysis suggests that living in high compared to low walkable neighbourhoods is associated with accumulating 766 more steps per day. Given that accumulating at least 10,000 steps per day is recommended for healthy adult populations [26], this is equivalent to approximately 8 % of recommended daily steps. While there is consistent evidence that higher neighbourhood walkability is associated with higher levels of biosensor-assessed walking in Europe and possibly in Asia, no comparable studies have been conducted in North America. Given higher levels of car ownership [52] and physical inactivity [53] in North America, the association between neighbourhood designs and the total amount of walking that people achieve may be different in this context. To increase our understanding of this relationship in North America, more studies using comparable measures of exposures and outcomes in this setting are needed.

Abbreviations

CI: Confidence interval; CrI: Credible interval.

Competing interests

There are no conflicts of interest to disclose.

Authors' contributions

SH conceived and developed the study, conducted the statistical analyses, and wrote the manuscript. KD and NR helped develop the study question and edited the manuscript for content. ASB assisted in the review of articles and reviewed the manuscript for content. LJ provided guidance regarding the statistical analyses and reviewed the manuscript for content. PB assisted with WinBUGS and R programming and reviewed the manuscript for content. All authors contributed to the interpretation of data, reviewed the manuscript for content, and approved the final manuscript for submission.

Acknowledgments

SH is supported by a Canadian Institutes of Health Research (CIHR) Doctoral Research Award. KD is supported through a Senior Clinician Scientist Award from the Fonds de Recherché Santé Québec (FRQ-S). ASB is supported by a post-doctoral fellowship from the Heart and Stroke Foundation.

Author details

[1]Department of Epidemiology, Biostatistics and Occupational Health, McGill University, 1020 Pine Avenue West, Montréal, QC, Canada. [2]Department of Geography, McGill University, 805 Sherbrooke Street West, Montréal, QC, Canada. [3]Department of Medicine, Division of Clinical Epidemiology, McGill University Health Centre, 687 Pine Avenue West, Montréal, QC, Canada.

Received: 20 March 2015 Accepted: 23 July 2015

References

1. Obesity and overweight. Fact sheet N°311. Geneva, Switzerland: Organization WH; 2015.
2. Roberto CA, Swinburn B, Hawkes C, Huang TT, Costa SA, Ashe M, et al. Patchy progress on obesity prevention: emerging examples, entrenched barriers, and new thinking. Lancet. 2015;18.
3. Finegood DT. The importance of systems thinking to address obesity. Nestle Nutr Inst Workshop Ser. 2012;73:123–37. discussion 39–41.
4. Sallis JF, Bauman A, Pratt M. Environmental and policy interventions to promote physical activity. Am J Prev Med. 1998;15(4):379–97. Comparative Study Review.
5. Ferdinand AO, Sen B, Rahurkar S, Engler S, Menachemi N. The relationship between built environments and physical activity: a systematic review. Am J Public Health. 2012;102(10):e7–e13. Research Support, U.S. Gov't, P.H.S. Review.
6. Ewing R, Cervero R. Travel and the built environment: A Meta-analysis. J Am Plan Assoc. 2010;76(3):265–94.
7. King AC, Stokols D, Talen E, Brassington GS, Killingsworth R. Theoretical approaches to the promotion of physical activity: forging a transdisciplinary paradigm. Am J Prev Med. 2002;23(2 Suppl):15–25.
8. Spence JC, Lee RE. Toward a comprehensive model of physical actovity. Psychol Sport Exerc. 2003;4:7–24.
9. Li F, Harmer P, Cardinal BJ, Bosworth M, Johnson-Shelton D. Obesity and the built environment: does the density of neighborhood fast-food outlets matter? Am J Health Promot. 2009;23(3):203–9.
10. Li F, Harmer P, Cardinal BJ, Bosworth M, Johnson-Shelton D, Moore JM, et al. Built environment and 1-year change in weight and waist circumference in middle-aged and older adults: Portland Neighborhood Environment and Health Study. Am J Epidemiol. 2009;169(4):401–8.
11. Cervero R, Kockelman K. Travel demand and the 3Ds: Density, diversity, and design. Transp Res Part D: Transp Environ. 1997;2(3):199–219.
12. Frank LD, Andresen MA, Schmid TL. Obesity relationships with community design, physical activity, and time spent in cars. Am J Prev Med. 2004;27(2):87–96.
13. Leslie E, Coffee N, Frank L, Owen N, Bauman A, Hugo G. Walkability of local communities: using geographic information systems to objectively assess relevant environmental attributes. Health Place. 2007;13(1):111–22.
14. Adams MA, Frank LD, Schipperijn J, Smith G, Chapman J, Christiansen LB, et al. International variation in neighborhood walkability, transit, and recreation environments using geographic information systems: the IPEN adult study. Int J Health Geogr. 2014;13:43.
15. Saelens BE, Sallis JF, Frank L. Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures. Ann Behav Med. 2003;25(2):80–91.
16. Manaugh K, Kreider T. What is mixed use? Presenting an interaction method for measuring land use mix. J Transp Land Use. 2013;6(1):63–72.
17. Hajna S, Dasgupta K, Joseph L, Ross NA. A call for caution and transparency in the calculation of land use mix: measurement bias in the estimation of associations between land use mix and physical activity. Health Place. 2014;29:79–83.
18. Frank LD, Schmid TL, Sallis JF, Chapman J, Saelens BE. Linking objectively measured physical activity with objectively measured urban form: findings from SMARTRAQ. Am J Prev Med. 2005;28(2 Suppl 2):117–25.
19. Cerin E, Leslie E, Du Toit L, Owen N, Frank LD. Destinations that matter: associations with walking for transport. Health Place. 2007;13(3):713–24.
20. Christiansen LB, Madsen T, Schipperijn J, Ersboll AK, Troelsen J. Variations in active transport behavior among different neighborhoods and across adult lifestages. J Transp Health. 2014;1(4):316–25.
21. Jack E, McCormack GR. The associations between objectively-determined and self-reported urban form characteristics and neighborhood-based walking in adults. Int J Behav Nutr Phys Act. 2014;11:71.
22. Tuckel P, Milczarski W. Walk Score (TM), Perceived Neighborhood Walkability, and walking in the US. Am J Health Behav. 2015;39(2):242–56.
23. Yates T, Haffner SM, Schulte PJ, Thomas L, Huffman KM, Bales CW, et al. Association between change in daily ambulatory activity and cardiovascular events in people with impaired glucose tolerance (NAVIGATOR trial): a cohort analysis. Lancet. 2013;19.
24. Gilmour H. Physically active Canadians. Health Rep. 2007;18(3):45–65.
25. Tudor-Locke C, Bassett DR, Swartz AM, Strath SJ, Parr BB, Reis JP, et al. A preliminary study of one year of pedometer self-monitoring. Ann Behav Med. 2004;28(3):158–62. Clinical Trial.
26. Tudor-Locke C, Bassett Jr DR. How many steps/day are enough? Preliminary pedometer indices for public health. Sports Med. 2004;34(1):1–8. Review.
27. Tudor-Locke C, Hatano Y, Pangrazi RP, Kang M. Revisiting "how many steps are enough?". Med Sci Sports Exerc. 2008;40(7 Suppl):S537–43.
28. Tudor-Locke CE, Bell RC, Myers AM, Harris SB, Lauzon N, Rodger NW. Pedometer-determined ambulatory activity in individuals with type 2 diabetes. Diabetes Res Clin Pract. 2002;55(3):191–9.
29. Moher D, Liberati A, Tetzlaff J, Altman DG, Group P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 2009;6(7), e1000097.
30. Van Dyck D, Deforche B, Cardon G, De Bourdeaudhuij I. Neighbourhood walkability and its particular importance for adults with a preference for passive transport. Health Place. 2009;15(2):496–504.
31. Van Dyck D, Cardon G, Deforche B, De Bourdeaudhuij I. Urban–rural differences in physical activity in Belgian adults and the importance of psychosocial factors. J Urban Health. 2011;88(1):154–67.
32. Dygryn J, Mitas J, Stelzer J. The influence of built environment on walkability using geographic information system. J Hum Kinet. 2010;24:93–9.
33. Robertson LB, Ward Thompson C, Aspinall P, Millington C, McAdam C, Mutrie N. The influence of the local neighbourhood environment on walking levels during the Walking for Wellbeing in the West pedometer-based community intervention. J Environ Public Health. 2012;2012:974786. Research Support, Non-U.S. Gov't.
34. Zhang Y, Liu ND, Liu X. Relationship Between Built Environment, Physical Activity, Adiposity and Health in Adults Aged 46–80 in Shanghai, China. J Phys Act Health. 2014;16.

35. Kondo K, Lee JS, Kawakubo K, Kataoka Y, Asami Y, Mori K, et al. Association between daily physical activity and neighborhood environments. Environ Health Prev Med. 2009;14(3):196–206.
36. Schneider PL, Crouter SE, Lukajic O, Bassett Jr DR. Accuracy and reliability of 10 pedometers for measuring steps over a 400-m walk. Med Sci Sports Exerc. 2003;35(10):1779–84.
37. Crouter SE, Schneider PL, Karabulut M, Bassett Jr DR. Validity of 10 electronic pedometers for measuring steps, distance, and energy cost. Med Sci Sports Exerc. 2003;35(8):1455–60.
38. Schneider PL, Crouter S, Bassett DR. Pedometer measures of free-living physical activity: comparison of 13 models. Med Sci Sports Exerc. 2004;36(2):331–5.
39. Welk GJ, Differding JA, Thompson RW, Blair SN, Dziura J, Hart P. The utility of the Digi-walker step counter to assess daily physical activity patterns. Med Sci Sports Exerc. 2000;32(9 Suppl):S481–8.
40. Holbrook EA, Barreira TV, Kang M. Validity and reliability of Omron pedometers for prescribed and self-paced walking. Med Sci Sports Exerc. 2009;41(3):670–4.
41. Le Masurier GC, Tudor-Locke C. Comparison of pedometer and accelerometer accuracy under controlled conditions. Med Sci Sports Exerc. 2003;35(5):867–71.
42. Leicht AS, Crowther RG. Influence of non-level walking on pedometer accuracy. J Sci Med Sport. 2009;12(3):361–5.
43. Dasgupta K, Joseph L, Pilote L, Strachan I, Sigal RJ, Chan C. Daily steps are low year-round and dip lower in fall/winter: findings from a longitudinal diabetes cohort. Cardiovasc Diabetol. 2010;9:81. Research Support, Non-U.S. Gov't.
44. Hamilton SL, Clemes SA, Griffiths PL. UK adults exhibit higher step counts in summer compared to winter months. Ann Hum Biol. 2008;35(2):154–69.
45. Cerin E, Cain KL, Conway TL, Van Dyck D, Hinckson E, Schipperijn J, et al. Neighborhood environments and objectively measured physical activity in 11 countries. Med Sci Sports Exerc. 2014;46(12):2253–64. Research Support, N.I.H., Extramural Research Support, Non-U.S. Gov't Research Support, U.S. Gov't, P.H.S.
46. McCormack GR, Shiell A. In search of causality: a systematic review of the relationship between the built environment and physical activity among adults. Int J Behav Nutr Phys Act. 2011;8:125. Research Support, Non-U.S. Gov't Review.
47. Humpel N, Owen N, Leslie E. Environmental factors associated with adults' participation in physical activity: a review. Am J Prev Med. 2002;22(3):188–99. Meta-Analysis.
48. McCormack G, Giles-Corti B, Lange A, Smith T, Martin K, Pikora TJ. An update of recent evidence of the relationship between objective and self-report measures of the physical environment and physical activity behaviours. J Sci Med Sport. 2004;7(1):81–92. Research Support, Non-U.S. Gov't Review.
49. Saelens BE, Handy SL. Built environment correlates of walking: a review. Med Sci Sports Exerc. 2008;40(7):S550–66. Research Support, N.I.H., Extramural Review.
50. De Cocker KA, De Bourdeaudhuij IM, Cardon GM. The effect of pedometer use in combination with cognitive and behavioral support materials to promote physical activity. Patient Educ Couns. 2008;70(2):209–14. Randomized Controlled Trial.
51. Ribeiro MA, Martins MA, Carvalho CR. Interventions to increase physical activity in middle-age women at the workplace: a randomized controlled trial. Med Sci Sports Exerc. 2014;46(5):1008–15. Randomized Controlled Trial Research Support, Non-U.S. Gov't.
52. The World Bank Group. Data: Motor vehicles (per 1,000 people). World Development Indicators, International Road Federation, World Road Statistics and Data Files. 2008;2015(February 17). 2015.
53. World Health Organization. Global Health Observatory: Prevalence of Insufficient Physical Activity. Geneva, Switzerland: World Health Organization; 2015 [cited 2015 February 17]; Available from: http://www.who.int/gho/ncd/risk_factors/physical_activity_text/en/index.html.

CHAPTER FOUR | Manuscript 2

Neighborhood walkability: Field validation of Geographic Information System Measures

Samantha Hajna,[1] Kaberi Dasgupta,[1,2] Max Halparin,[3] Nancy A. Ross[1,3]

Am J Prev Med, 2013;44(6):e51-e55

[1] Department of Epidemiology, Biostatistics and Occupational Health,
McGill University, 1020 Pine Avenue West, Montreal, QC, Canada.

[2] Department of Medicine, Division of Clinical Epidemiology,
McGill University Health Centre, 687 Pine Avenue West, Montreal, QC, Canada.

[3] Department of Geography, McGill University,
805 Sherbrooke Street West, Montreal, QC, Canada.

PREAMBLE

In Chapter 3 I presented the results of my first study (*Manuscript 1*). In this study, I determined that Belgian, Czech and Japanese adults who live in high compared to low walkable neighbourhoods accumulate 766 more steps/day (95% CrI 250, 1271). This is a clinically important amount as it accounts for approximately 8% of recommended daily steps. In *Manuscript 1* (Chapter 3) I also identified the need for comparable studies to be conducted in North America.

Before proceeding with my substantive work there were two methodological issues that I first wanted to explore. First, although GIS-derived measures of street connectivity, land use mix, and residential and/or population density are commonly used as measures of neighbourhood walkability, field validation of these measures is limited. Second, there is evidence that the Shannon entropy formula that is a commonly used to calculate land use mix has been misspecified in previous studies. In this chapter (*Manuscript 2*), I address the first limitation by assessing the degree to which GIS-derived street connectivity, land use mix, and residential density (both individually and as a composite index of neighbourhood walkability) correlate with an in-field audit. I also examined the associations of these researcher-assessed methods with participants' perceptions of their home neighbourhoods. In Chapter 5 (*Manuscript 3*) I address the second methodological limitation. The study presented in this chapter (*Manuscript 2*) has been published in the *American Journal of Preventative Medicine* **(Hajna et al., 2013;44(6):e51-e55).** Please note that all of the supplementary files referenced in this manuscript are included in Appendix D.

Neighborhood Walkability
Field Validation of Geographic Information System Measures

Samantha Hajna, MSc, Kaberi Dasgupta, MD, MSc, FRCPC, Max Halparin, BA, Nancy A. Ross, PhD

Background: Given the health benefits of walking, there is interest in understanding how physical environments favor walking. Although GIS-derived measures of land-use mix, street connectivity, and residential density are commonly combined into indices to assess how conducive neighborhoods are to walking, field validation of these measures is limited.

Purpose: To assess the relationship between audit- and GIS-derived measures of overall neighborhood walkability and between objective (audit- and GIS-derived) and participant-reported measures of walkability.

Methods: Walkability assessments were conducted in 2009. Street-level audits were conducted using a modified version of the Pedestrian Environmental Data Scan. GIS analyses were used to derive land-use mix, street connectivity, and residential density. Participant perceptions were assessed using a self-administered questionnaire. Audit, GIS, and participant-reported indices of walkability were calculated. Spearman correlation coefficients were used to assess the relationships between measures. All analyses were conducted in 2012.

Results: The correlation between audit- and GIS-derived measures of overall walkability was high (R=0.7 [95% CI=0.6, 0.8]); the correlations between objective (audit and GIS-derived) and participant-reported measures were low (R=0.2 [95% CI=0.06, 0.3]; R=0.2 [95% CI=0.04, 0.3], respectively). For comparable audit and participant-reported items, correlations were higher for items that appeared more objective (e.g., sidewalk presence, R=0.4 [95% CI=0.3, 0.5], versus safety, R=0.1 [95% CI=0.003, 0.3]).

Conclusions: The GIS-derived measure of walkability correlated well with the in-field audit, suggesting that it is reasonable to use GIS-derived measures in place of more labor-intensive audits. Interestingly, neither audit- nor GIS-derived measures correlated well with participants' perceptions of walkability.

(Am J Prev Med 2013;44(6):e55–e59) © 2013 American Journal of Preventive Medicine

---

Introduction

The global prevalence of physical activity is alarmingly low.[1] To facilitate population-level increases in physical activity, understanding how urban designs affect physical activity behavior is important.[2,3] Although GIS-derived measures of land-use mix, street connectivity, and residential density[3–6] are commonly combined into indices to capture the overall degree to which neighborhoods are conducive to walking, the criterion-related validity of these measures is unknown. The aims of the current study were to assess the relationships between audit- and GIS-derived measures of overall neighborhood walkability, where street-level audits are considered the gold standard in environmental assessment, and between objective (audit- and GIS-derived) and participant-reported measures of neighborhood walkability.

Methods

Walkability assessments were conducted in 2009 on 200 Montréal (Quebec, Canada; Figure 1) neighborhoods. All participants were adults from these neighborhoods who had type 2 diabetes and who

---

From the Department of Epidemiology, Biostatistics and Occupational Health (Hajna, Dasgupta, Ross), the Department of Medicine, Division of Clinical Epidemiology (Dasgupta), and the Department of Geography (Ross, Halparin), McGill University Health Centre, McGill University, Montréal, Quebec, Canada

Address correspondence to: Nancy A. Ross, PhD, McGill University, Department of Geography, 805 Sherbrooke Street West, Montréal, QC H3A 2K6 Canada. E-mail: nancy.ross@mcgill.ca.

0749-3797/$36.00
http://dx.doi.org/10.1016/j.amepre.2013.01.033

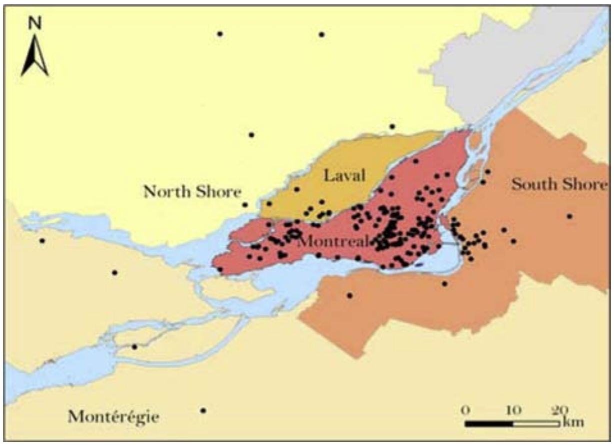


Figure 1. Locations of the neighborhoods on which audit, GIS, and participant-reported assessments were conducted

participated in a longitudinal study of walking and vascular disease risk.[7–10] Ethics approval was obtained from McGill University's Faculty of Medicine IRB.

Neighborhood Audits

Five street segments located within 500 meters of the centroid of each participant's home postal code were selected randomly and audited by research assistants (blinded to the GIS-derived measures) using a 21-item modified version of the Pedestrian Environmental Data Scan (PEDS; Appendix A).[11] Based on a priori analyses, a five-street segment sampling strategy was found to adequately capture the neighborhood characteristics of interest.

Geographic Information System–Derived Assessments

Polygonal buffers of 500 meters were constructed around the centroid of each participant's home postal code. Land-use mix, street connectivity, and residential density were derived for each buffer using ArcGIS 10.1. Land-use mix was based on an entropy score (higher score implied greater diversity).[12] Street connectivity equaled the number of four- or more-way intersections per square kilometer. Residential density equaled the number of residences per square kilometer of residential land area.

Participant Reports

Perceptions of walkability were assessed using nine items derived from three previously used surveys (Appendix B).[13]

Data Analysis

Indices of walkability were calculated by summing and standardizing the responses of the audit and survey items onto scales of 0 to 1. The GIS-derived walkability index was calculated by summing the *z*-scores of the three GIS-derived variables.[3–6] Higher index scores represented greater walkability. Correlations between measures were assessed using Spearman correlation coefficients (R). Principal components analyses with varimax rotations were used to identify key factors in the audit and survey tools. Regression-based factor scores were summed to produce audit and participant-reported indices of overall walkability. Sensitivity analyses were conducted to determine if use of regression-based factor scores altered study findings. All analyses were performed in 2012 using SAS 9.2.

Results

The audit walkability index ranged from 0.30 to 0.71 (M=0.50, SD 0.08 [95% CI=0.47, 0.49]); the GIS-derived walkability index ranged from −4.35 to 6.55 (M=0, SD 2.36 [95% CI=−0.33, 0.33]); and the participant-reported walkability index ranged from 0.15 to 1.00 (M=0.74, SD 0.15 [95% CI=0.72, 0.76]). The inter-rater agreement in audit-based assessments was high (Pearson correlation coefficient=0.95 [95% CI=0.94, 0.97]). A total of 199 participants (99.5%) completed the neighborhood survey. Respondents were aged 59.8 years (±10.4). Respondents were mostly female (53.0%); university educated (39.0%); and Europid (69.0%).

Audit- and GIS-derived walkability were highly correlated (Table 1). Moderate to high correlations were observed between audit-derived walkability and GIS-derived land-use mix, street connectivity, and residential density; and between audit- and GIS-derived land-use mix (Table 1). Low correlations were observed between participant-reported walkability and GIS-derived walkability, land-use mix, street connectivity, and residential density; and between comparable participant-reported, audit- and GIS-derived items (Table 1). For comparable audit and participant-reported items, correlations were higher for items that appeared more objective (e.g., sidewalk presence versus safety) (Table 1). Correlations between GIS-derived measures were moderate (residential density versus land-use mix R=0.6 [95% CI=0.5, 0.7]; residential density versus street connectivity R=0.6 [95% CI=0.5, 0.7]; land-use mix versus street connectivity R=0.4 [95% CI=0.3, 0.5].

Three factors accounting for 73% of the variance in the retained items were identified in the audit tool (amenities, neighborhood aesthetics and safety, sidewalks; Table 2). Three factors accounting for 59% of the total variance were identified in the survey tool (amenities, neighborhood aesthetics and activity, and safety; Appendix C). No differences in correlations were observed when using factor scores.

Discussion

Audit- and GIS-derived measures of walkability were highly correlated, suggesting that GIS-derived measures can be used in place of labor-intensive neighborhood auditing. Residential density correlated most with overall audit-derived walkability, suggesting that residential density alone may be an adequate proxy for in-field audits. Audit- and GIS-derived land-use mix were more weakly

Table 1. Correlations between audit, GIS, and participant-reported measures of neighborhood walkability

GIS measure	Audit measure	R (95% CI)[a]
Walkability	Walkability	0.7 (0.6, 0.8)
Land-use mix	Walkability	0.5 (0.4, 0.6)
Street connectivity	Walkability	0.6 (0.5, 0.7)
Residential density	Walkability	0.7 (0.6, 0.8)
Land-use mix	Number of land uses	0.5 (0.4, 0.6)
GIS measure (objective)[b]	**Participant-reported measure[b]**	**R (95% CI)[a]**
Walkability	Walkability	0.2 (0.04, 0.3)
Land-use mix	Walkability	0.2 (0.1, 0.3)
Street connectivity	Walkability	0.1 (−0.02, 0.3)
Residential density	Walkability	0.2 (0.1, 0.3)
Residential density	Stores within walking distance	0.4 (0.2, 0.5)
Audit measure	**Participant-reported measure**	**R (95% CI)[a]**
Walkability	Walkability	0.2 (0.06, 0.3)
Sidewalk presence	Sidewalk presence	0.4 (0.3, 0.5)
Sidewalk conditions	Sidewalk conditions	0.3 (0.2, 0.4)
Pedestrian lighting	Street lighting conditions	0.2 (0.1, 0.3)
Roadway lighting	Street lighting conditions	0.2 (0.1, 0.3)
Number of land uses	Stores within walking distance	0.2 (0.1, 0.4)
Bus stop or metro	Easy walk, transit stop	0.2 (0.04, 0.3)
Safe	Safe	0.1 (0.003, 0.3)

[a] Spearman correlation coefficients
[b] Based on a sample size of 199

correlated, likely because audits are limited in their ability to assess factors that are not restricted to a street view. For variables such as land-use mix, the "bird's-eye view" provided by GIS may be more informative that an in-field audit. Low correlations were observed between objective and participant-reported measures, suggesting that they capture different constructs.

Two previous studies examined the concordance between audit- and GIS-derived measures of walkability,[13,14] but to our knowledge, this is the first study to quantify the correlation between these two measures. Several previous studies also have examined the validity of GIS-derived measures of specific neighborhood characteristics.[14–17] In contrast to the high correlations observed herein, most of these studies reported low to moderate concordances between measures.[14–16] The difference may be because the focus in the current study was on urban design factors, whereas the focus in previous studies has been on small-scale characteristics (e.g., presence of food outlets[16]). Because maintaining spatial files on small-scale factors is more challenging because of their dynamic nature, it is not surprising that lower correlations were observed.

Although use of participant-reported measures may be important for understanding certain types of physical activity (e.g., leisure-time physical activity),[18,19] the unique challenges associated with these measures should not be overlooked. First, because increased physical activity may lead to better perceptions and better perceptions also may lead to higher levels of physical activity, disentangling the directionality of the relationship in cross-sectional studies is challenging. Second, the population-level impact of interventions aimed at improving perceptions is limited.

Arguably, the greatest improvements to public health have come through environmental changes (e.g., sanitation reform in 19th-century England,[20] tobacco sale restrictions[21]). In line with this perspective, it is proposed here that designing neighborhoods that are supportive of physical activity will have the largest impact on facilitating population-level increases in physical activity and that when these walkable neighborhoods are designed, individual-level interventions also will be more likely to succeed. This is because, even though individuals must first recognize the importance of physical activity, in the absence of choice-enabling environments, volitional attempts at increasing physical activity will be met with limited success. For physical activity interventions to reach their peak effectiveness, both individual perceptions and the built environment should be targeted.

Limitations

Two study limitations must be addressed. One consideration is that although audit and GIS measures were compared, there was a lack of alignment between the items

Table 2. Eigenvalues (EV) and factor loadings from the principal components analysis of the items that were assessed using the modified version of the Pedestrian Environmental Data Scan[a]

Item		Factor 1: amenities (4.16)	Factor 2: neighborhood aesthetics and safety (1.99)	Factor 3: sidewalks (1.16)
1	Number of land uses	0.84[b]	−0.15	0.15
2	Sidewalk presence	0.33	−0.16	0.89[b]
3	Sidewalk condition	0.22	0.03	0.94[b]
4	Crossing aids	0.63[b]	−0.01	0.27
5	Street amenities	0.80[b]	0.09	0.20
6	Articulation in building designs	0.24	0.81[b]	−0.01
7	Bus stops or metro	0.56[b]	−0.23	0.08
8	Attractiveness	−0.20	0.88[b]	−0.13
9	Safety	−0.36	0.81[b]	0.00
10	Utilitarian	0.89[b]	−0.07	0.22

Note: Eigenvalues are shown in parentheses following column headings.

[a] Several of the original audit items ($n=11$) were removed during the principal components analyses because they overlapped with another factor and thus could not contribute uniquely to any one factor. The removed items included slope steepness, buffers between road and sidewalk, sidewalk width, number of lanes, number of trees shading walking area, overall cleanliness and maintenance, pedestrian lighting, roadway lighting, green space, medium- to high-volume driveways, and traffic control devices.

[b] Factor loadings ≥ 0.40

assessed by these tools. However, the primary aim of this study was to examine the correlation between overall measures of walkability using these tools. A high correlation between audit- and GIS-derived walkability was demonstrated, suggesting that although these tools assess walkability in different ways, the final picture is similar. Second, survey respondents had diabetes mellitus 2, a metabolic disorder that affects blood glucose control and places individuals at an increased risk for various health complications,[22] including depressive symptoms.[23] Because the perceptions of this population may differ from those of the general population, the correlations between perceived and objective measures may be lower than those that would have been observed in the general population.

Conclusion

This study provides evidence that GIS-derived measures can be used in place of labor-intensive neighborhood auditing. Neither audit- nor GIS-derived measures correlated well with participants' perceptions of walkability, suggesting that these measures capture different constructs that may affect walking differently. Further research on the differential role of these measures in predicting physical activity is warranted.

This study was funded by grants from the Canadian Institutes of Health Research (CIHR) (KD, MOP-79275; NR). SH is supported through a CIHR Doctoral Research Award. Support to SH was provided also through a CIHR Interdisciplinary Capacity Enhanced Team Grant (HOA-80072). KD is supported through the Fonds de recherché Sante Québec-Société québécoise d'hypertension arterielle (SQHA)-Jacques de Champlain Clinician Scientist Award. NR was supported by a Fonds de recherché Sante Québec (FRSQ) Career Award (Chercheurs Boursier Health and Society). The authors thank Max Halparin, Alexandre Poisson, and Elizabeth McNamee for conducting the neighborhood audits.

Samantha Hajna is supported by a Canadian Institutes of Health Research (CIHR) Doctoral Research Award. Support also was provided through a CIHR Interdisciplinary Capacity Enhanced Team Grant (HOA-80072). Dr. Kaberi Dasgupta is Associate Professor of Medicine at McGill University. She holds the Fonds de recherché Sante Québec-Société québécoise d'hypertension arterielle (SQHA)-Jacques de Champlain Clinician Scientist Career Award. Data collection for this study was funded by a Canadian Institutes of Health Research (CIHR) Catalyst Grant to Dr. Nancy Ross and Dr. Dasgupta (94431) and an operating grant from CIHR awarded to Dr. Dasgupta (MOP-79275).

No financial disclosures were reported by the authors of this paper.

References

1. WHO. Global health observatory: prevalence of insufficient physical activity. 2012. www.who.int/gho/ncd/risk_factors/physical_activity_text/en/index.html.

2. Frank LD, Kerr J, Sallis JF, Miles R, Chapman J. A hierarchy of sociodemographic and environmental correlates of walking and obesity. Prev Med 2008;47(2):172–8.
3. Sundquist K, Eriksson U, Kawakami N, Skog L, Ohlsson H, Arvidsson D. Neighborhood walkability, physical activity, and walking behavior: the Swedish Neighborhood and Physical Activity (SNAP) study. Soc Sci Med 2011;72(8):1266–73.
4. De Meester F, Van Dyck D, De Bourdeaudhuij I, Deforche B, Sallis JF, Cardon G. Active living neighborhoods: is neighborhood walkability a key element for Belgian adolescents? BMC Public Health 2012;12:7.
5. Van Dyck D, Cardon G, Deforche B, Sallis JF, Owen N, De Bourdeaudhuij I. Neighborhood SES and walkability are related to physical activity behavior in Belgian adults. Prev Med. Jan 2010;50(S1):S74–S79.
6. Frank LD, Schmid TL, Sallis JF, Chapman J, Saelens BE. Linking objectively measured physical activity with objectively measured urban form: findings from SMARTRAQ. Am J Prev Med 2005;28(2S2):117–25.
7. Manjoo P, Joseph L, Dasgupta K. Abdominal adiposity and daily step counts as determinants of glycemic control in a cohort of patients with type 2 diabetes mellitus. Nutr Diabetes 2012;2:e25.
8. Dasgupta K, Joseph L, Pilote L, Strachan I, Sigal RJ, Chan C. Daily steps are low year-round and dip lower in fall/winter: findings from a longitudinal diabetes cohort. Cardiovasc Diabetol 2010;9:81.
9. Manjoo P, Joseph L, Pilote L, Dasgupta K. Sex differences in step count-blood pressure association: a preliminary study in type 2 diabetes. PLoS One 2010;5(11):e14086.
10. Dasgupta K, Chan C, Da Costa D, et al. Walking behaviour and glycemic control in type 2 diabetes: seasonal and gender differences—study design and methods. Cardiovasc Diabetol 2007;6:1.
11. Clifton KJ, Smith LA, Rodriguez D. The development and testing of an audit for the pedestrian environment. Landscape Urban Plann 2007;80(1–2):95–110.
12. Leslie E, Coffee N, Frank L, Owen N, Bauman A, Hugo G. Walkability of local communities: using geographic information systems to objectively assess relevant environmental attributes. Health Place 2007;13(1):111–22.
13. Brownson RC, Chang JJ, Eyler AA, et al. Measuring the environment for friendliness toward physical activity: a comparison of the reliability of 3 questionnaires. Am J Public Health 2004;94(3):473–83.
14. Zandbergen PA, Chakraborty J. Improving environmental exposure analysis using cumulative distribution functions and individual geocoding. Int J Health Geogr 2006;5:23.
15. Patterson L, Urban M, Myers A, Bhaduri B, Bright E, Coleman P. Assessing spatial and attribute errors in large national datasets for population distribution models: a case study of Philadelphia county schools. GeoJournal 2007;69:93–102.
16. Liese AD, Colabianchi N, Lamichhane AP, et al. Validation of 3 food outlet databases: completeness and geospatial accuracy in rural and urban food environments. Am J Epidemiol 2010;172(11): 1324–33.
17. Purciel M, Neckerman KM, Lovasi GS, et al. Creating and validating GIS measures of urban design for health research. J Environ Psychol 2009;29:457–66.
18. Hoehner CM, Brennan Ramirez LK, Elliott MB, Handy SL, Brownson RC. Perceived and objective environmental measures and physical activity among urban adults. Am J Prev Med 2005;28(2S2):105–16.
19. Cao X, Handy SL, Mokhtarian PL. The influences of the built environment and residential self-selection on pedestrian behavior: evidence from Austin, TX. Transportation 2006;33:1–20.
20. Sir Edwin Chadwick (1800-1890) sanitarian and social reformer JAMA 1968;203(1):45–6.
21. WHO. WHO framework convention on tobacco control. Geneva, Switzerland: WHO Document Production Services, 2003. ISBN 9241591013.
22. American Diabetes Association. Diagnosis and classification of diabetes mellitus. Diabetes Care 2012;35(S1):S64–S71.
23. Roy T, Lloyd CE. Epidemiology of depression and diabetes: a systematic review. J Affect Disord 2012;142(S):S8–S21.

Appendix

Supplementary data

Supplementary data associated with this article can be found at http://dx.doi.org/10.1016/j.amepre.2013.01.033.

CHAPTER FIVE | Manuscript 3

A call for caution and transparency in the calculation of land use mix: Measurement bias in the estimation of associations between land use mix and physical activity

Samantha Hajna,[1] Nancy A. Ross,[1,3] Lawrence Joseph,[1,2] Kaberi Dasgupta[1,2]

Health & Place. 2014; 29: 79-83

[1] Department of Epidemiology, Biostatistics and Occupational Health,
McGill University, 1020 Pine Avenue West, Montreal, QC, Canada.

[2] Department of Medicine, Division of Clinical Epidemiology,
McGill University Health Centre, 687 Pine Avenue West, Montreal, QC, Canada.

[3] Department of Geography, McGill University,
805 Sherbrooke Street West, Montreal, QC, Canada.

PREAMBLE

In Chapter 4 I presented the results of my study (*Manuscript 2*) in which I validated the GIS-derived measures of street connectivity, land use mix, and residential and/or population density that I would be using in my main substantive studies (*Manuscripts 3, 4* and *5*). In this study, I demonstrated that GIS-derived measures of walkability correlated well with in-field audits, suggesting that their use as measures of walkability is justified. I also demonstrated that neither in-field audits nor GIS-derived measures correlated well with participants' perceptions of walkability. This suggests that researcher-assessed measures of walkability capture a different component of walkability than participant-reported measures do.

In preparing this validation piece, I found evidence that the formula that is commonly used to assess land use mix may have been misspecified in some studies. Since I was proposing to use this measure in my three substantive pieces, I wanted to ensure that I was using it appropriately. My aim in the study that I present in this chapter (*Manuscript 3*) was to quantify the amount of bias that would arise from the misspecification of this formula. Given that this field is growing and this measure is being used with increasing frequency, my goal was also to alert researchers to this potential source of bias and to encourage them to use caution in the calculation of land use mix. This study was published in *Health & Place* **(Hajna et al., 2014; 29: 79-83).**

Health & Place 29 (2014) 79–83

Contents lists available at ScienceDirect

Health & Place

journal homepage: www.elsevier.com/locate/healthplace

A call for caution and transparency in the calculation of land use mix: Measurement bias in the estimation of associations between land use mix and physical activity

Samantha Hajna [a], Kaberi Dasgupta [a,b,*], Lawrence Joseph [a,b], Nancy A. Ross [a,c]

[a] Department of Epidemiology, Biostatistics and Occupational Health, McGill University, 1020 Pine Avenue West, Montréal, QC, Canada
[b] Department of Medicine, Division of Clinical Epidemiology, McGill University Health Centre, 687 Pine Avenue West, Montréal, QC, Canada
[c] Department of Geography, McGill University, 805 Sherbrooke Street West, Montréal, QC, Canada

ARTICLE INFO

Article history:
Received 28 March 2014
Received in revised form
3 June 2014
Accepted 10 June 2014
Available online 3 July 2014

Keywords:
Land use mix
Measurement bias
Walking
Physical activity

ABSTRACT

There is evidence that land use mix based on the Shannon (1948) entropy formula may be misspecified in some studies. The aim of this study was to quantify the bias arising from this misspecification. Spatial coordinates were obtained from Statistics Canada for 9348 unique point locations. Five hundred-metre polygon-based network buffers were drawn around each coordinate (ArcGIS 10.1). Land use mix was calculated for each buffer using the true and misspecified land use mix formulas. Linear regression models were used to estimate the associations between a simulated dataset of daily steps and the true and misspecified measures. Misspecification of the land use mix formula resulted in a systematic underestimation of the true association by 26.4% (95% CI 25.8–27.0%). To minimize measurement bias in future studies, researchers are encouraged to use a constant definition of N in the denominator of the Shannon entropy formula.

1. Introduction

In the last decade there has been an increase in the number of studies conducted on the associations between neighbourhood designs and physical activity (Ding and Gebel, 2012; Feng et al., 2010). Recent reviews have highlighted inconsistencies across studies, with variability in demonstrated effects (Feng et al., 2010; McCormack and Shiell, 2011; Ferdinand et al., 2012). While the important contributory factors that constitute walkability are conceptually well-defined, inconsistencies in their associations with physical activity may be partly attributable to differences in walkability measurement and computation of indices (Hess et al., 2001; Brownson et al., 2009). One example of this is in the current method of calculating land use mix – a component of walkability.

Land use mix is a measure of the diversity of land uses contained in a neighbourhood (Leslie et al., 2007; Manaugh and Kreider, 2013). While many studies suggest that higher land use mix is associated with higher levels of physical activity, others suggest null effects (Feng et al., 2010; McCormack and Shiell, 2011; Grasser et al., 2013). In the neighbourhoods and health literature, land use mix is most commonly calculated using a variation of an entropy formula introduced in 1948 by Claude E. Shannon as part of his work on the mathematical theory of communication (Shannon, 1948). It is defined as $(-\sum_k (p_k \ln p_k))/\ln N$, where p is the proportion of land area within a predefined geographical zone devoted to a specific land use and N is the total number of land use categories (Leslie et al., 2007; Manaugh and Kreider, 2013). The resulting values range from 0 to 1 where 0 represents complete homogeneity and 1 represents complete heterogeneity in land uses within a neighbourhood.

When calculating land use mix via the Shannon entropy formula, the value of N should remain constant. Misspecification of the entropy formula arises when N is defined as the number of land uses that fall into each neighbourhood buffer (i.e., variable for each neighbourhood). This is problematic as it results in an overestimation of land use mix in some neighbourhoods and does not allow for meaningful comparisons of land use mix within a study. Take, for example two hypothetical neighbourhoods, for simplicity defined here by polygonal buffers around two home addresses (Fig. 1). Neighbourhood A is comprised of two types of land uses (i.e., residential and commercial) while Neighbourhood B is comprised of three types of land uses (i.e., residential, commercial and governmental). Assuming that there are three land uses of interest in total, Neighbourhood A should have an entropy score less than 1, and Neighbourhood B should have an entropy score equal to 1 (i.e., the most amount of diversity in land uses possible given three land uses

---

[*] Corresponding author at: McGill University, Division of Clinical Epidemiology, Department of Medicine, McGill University Health Centre, 687 Pine Avenue West, V1.08, Montréal, QC, Canada. Tel.: +1 514 934 1934x44715; fax: +1 514 934 8293.
E-mail addresses: samantha.hajna@mail.mcgill.ca (S. Hajna), kaberi.dasgupta@mcgill.ca (K. Dasgupta), lawrence.joseph@mcgill.ca (L. Joseph), nancy.ross@mcgill.ca (N.A. Ross).

http://dx.doi.org/10.1016/j.healthplace.2014.06.002
1353-8292/© 2014 Elsevier Ltd. All rights reserved.

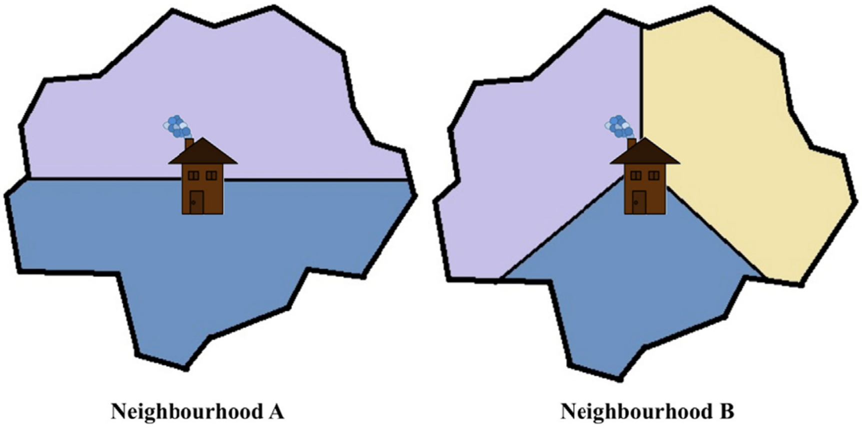


Fig. 1. Two hypothetical neighbourhoods with one representing a 50–50% split between two types of land uses (Neighbourhood A) and one representing a 33–33% split between three types of land uses (Neighbourhood B).

of interest). However, when N is defined as the number of land uses in each buffer (i.e., 2 for Neighbourhood A; 3 for Neighbourhood B), the resulting entropy scores for Neighbourhoods A and B are both 1 – an overestimation of the land use mix in Neighbourhood A.[1] It is only when N is constant and equivalent to the *total* number of land uses of interest (i.e., 3) that meaningful comparisons of land use mix can be made across neighbourhoods within a study. In this example, use of a constant N results in entropy scores of 0.63 and 1 for Neighbourhoods A and B, respectively[2] – a more accurate reflection of the diversity of land uses in each of the neighbourhoods.

While previous studies may have used a constant definition of N (Frank et al., 2004; Hajna et al., 2013; Frank et al., 2007; Coffee et al., 2013), because N has not been explicitly defined in some studies and there is evidence that a variable definition of N may have been used (Frank et al., 2005, 2006), the possibility of exposure misclassification arising from the incorrect calculation of entropy cannot be ignored. The objective of this study was to quantify the amount of bias arising from using a variable definition of N in the Shannon entropy formula and to argue that careful consideration of how the entropy score is calculated is required in future studies.

2. Methods

2.1. Data

Anonymized spatial coordinates were obtained from Statistics Canada for 9348 unique point locations from across Canada. The point locations corresponded to the postal code addresses of individuals who participated in Cycle 1 (2007–2009) of the Canadian Health Measures Survey. The Canadian Measures Survey is a survey conducted on a nationally representative sample of Canadians aged 6–79 years. Individuals living on reserves, in institutions and full-time members of the Canadian Forces were not represented in the sample Statistics Canada (2011). Access to the data was granted by Statistics Canada.

2.2. Exposure measurement: land use mix

Neighbourhoods were approximated using 500-m polygon-based network buffers drawn around each point location (ArcGIS 10.1; ESRI; Redlands, CA). The areas of four land uses, identified *a priori* as important predictors walking, were calculated for each buffer. These included residential, commercial, institutional-governmental, and recreational land uses. Land uses that were not considered important predictors of walking were excluded (open/vacant, industrial, agricultural, railway, transportation and utility land) (Christian et al., 2011).

Land use mix was calculated for each neighbourhood buffer using a constant and a variable definition of N in the denominator of the Shannon entropy formula (herein referred to as $\text{LUM}_{\text{constant}}$ and $\text{LUM}_{\text{variable}}$, respectively). For both measures, the numerator was equal to $(-1)\sum_k(p_k \ln p_k)$ where p was the proportion of land area devoted to a specific land use (k) in the polygon-based network buffers (Leslie et al., 2007). For $\text{LUM}_{\text{constant}}$, the numerator was divided by ln(4), representing the four land uses of interest. For $\text{LUM}_{\text{variable}}$, the numerator was divided by ln(N), where N represented the number of the land types that fell into each buffer (i.e., 0, 1, 2, 3 or 4).

2.3. Outcome measurement: simulated daily step counts

Walking is the most common and preferred form of physical activity among adults (Gilmour, 2007). It is commonly assessed using pedometers, small devices that are worn on the hip and that capture the number of steps taken (Tudor-Locke et al., 2011; Marshall et al., 2009; Schneider et al., 2004). Daily step counts reflect overall physical activity levels in adults (Marshall et al., 2009)). Cut-points developed by Tudor-Locke and Bassett are commonly used to classify the activity levels of adults (sedentary: <5000 steps/day; low active: 5000–7499 steps/day; somewhat active: 7500–9999 steps/day; active: 10,000–12,500 steps/day; highly active: $>12{,}500$ steps/day) (Tudor-Locke and Bassett, 2004). Because higher daily steps counts have been linked to important health outcomes, including lower blood pressure, haemoglobin A1C, and anthropometric measures (Manjoo et al., 2010, 2012; Dwyer et al., 2011), they are an outcome of interest in the neighbourhood and health literature.

Data from Cycle 1 (2007–2009) of the Canadian Health Measures Survey indicate that, on average, Canadian men and women accumulate 9544 and 8385 steps/day, respectively (Colley et al., 2011) – placing them in the '*somewhat active*' category. Assuming that Canadian adults accumulate an average of 7000 steps/day when land use mix is zero, we created four linear regression models with varying assumptions regarding the associations between steps/day and the true land use mix score (i.e., $\text{LUM}_{\text{constant}}$). These included a 1000, 2000 and 3000 decrement in daily counts, a null effect, and a 1000, 2000 and 3000 increment in steps/day when comparing

---

[1] Land use mix (Neighbourhood A) $= -1((0.5 \ln 0.5)+(0.5 \ln 0.5)/\ln 2)=1$; land use mix (Neighbourhood B) $= -1((0.33 \ln 0.33)+(0.33 \ln 0.33)+(0.33 \ln 0.33)/\ln 3)=1$.

[2] Land use mix (Neighbourhood A) $= -1((0.5 \ln 0.5)+(0.5 \ln 0.5)/\ln 3)=0.63$; land use mix (Neighbourhood B) $= -1((0.33 \ln 0.33)+(0.33 \ln 0.33)+(0.33 \ln 0.33)/\ln 3)=1$; *Note:* The third term in the numerator is omitted given that the third land use is not present in the buffer and taking the natural logarithm of 0 is invalid.

Table 1
Per cent underestimation of steps/day by $\text{LUM}_{\text{variable}}$, overall and by rural/urban location.

Model ($y=\alpha+\beta x$)	**Increment in daily step counts (95% CI)**		**Percent underestimation** (95% CI)
	$\text{LUM}_{\text{constant}}$ standard	**$\text{LUM}_{\text{variable}}$** biased association	
Overall			
Steps = 7000 − 3000 ($\text{LUM}_{\text{constant}}$)	−3000	−2209 (−2226 to −2191)	26.4% (25.8–27.0)
Steps = 7000 − 2000 ($\text{LUM}_{\text{constant}}$)	−2000	−1472 (−1484 to −1461)	26.4% (25.8–27.0)
Steps = 7000 − 1000 ($\text{LUM}_{\text{constant}}$)	−1000	−736 (−742 to −730)	26.4% (25.8–27.0)
Steps = 7000 + 0 ($\text{LUM}_{\text{constant}}$)	0	0 (0–0)	0
Steps = 7000 + 1000 ($\text{LUM}_{\text{constant}}$)	1000	736 (730–742)	26.4% (25.8–27.0)
Steps = 7000 + 2000 ($\text{LUM}_{\text{constant}}$)	2000	1472 (1461–1484)	26.4% (25.8–27.0)
Steps = 7000 + 3000 ($\text{LUM}_{\text{constant}}$)	3000	2209 (2191–2226)	26.4% (25.8–27.0)
By location			
Rural: steps = 7000 − 3000 ($\text{LUM}_{\text{constant}}$)	−3000	−1982 (−2024 to −1940)	33.9% (32.5–35.3)
Urban: steps = 7000 − 3000 ($\text{LUM}_{\text{constant}}$)	−3000	−2208 (−2227 to −2189)	26.4% (25.8–27.0)
Rural: steps = 7000 − 2000 ($\text{LUM}_{\text{constant}}$)	−2000	−1321 (−1349 to −1293)	34.0% (32.5–35.4)
Urban: steps = 7000 − 2000 ($\text{LUM}_{\text{constant}}$)	−2000	−1472 (−1485 to −1459)	26.4% (25.8–27.1)
Rural: steps = 7000 − 1000 ($\text{LUM}_{\text{constant}}$)	−1000	−661 (−675 to −647)	33.9% (32.5–35.3)
Urban: steps = 7000 − 1000 ($\text{LUM}_{\text{constant}}$)	−1000	−736 (−742 to −730)	26.4% (25.8–27.0)
Rural: steps = 7000 + 0 ($\text{LUM}_{\text{constant}}$)	0	0 (0–0)	0
Urban: steps = 7000 + 0 ($\text{LUM}_{\text{constant}}$)	0	0 (0–0)	0
Rural: steps = 7000 + 1000 ($\text{LUM}_{\text{constant}}$)	1000	661 (647–675)	33.9% (32.5–35.3)
Urban: steps = 7000 + 1000 ($\text{LUM}_{\text{constant}}$)	1000	736 (730–742)	26.4% (25.8–27.0)
Rural: steps = 7000 + 2000 ($\text{LUM}_{\text{constant}}$)	2000	1321 (1293–1349)	34.0% (32.5–35.4)
Urban: steps = 7000 + 2000 ($\text{LUM}_{\text{constant}}$)	2000	1472 (1459–1485)	26.4% (25.8–27.1)
Rural: steps = 7000 + 3000 ($\text{LUM}_{\text{constant}}$)	3000	1982 (1940–2024)	33.9% (32.5–35.3)
Urban: steps = 7000 + 3000 ($\text{LUM}_{\text{constant}}$)	3000	2208 (2189–2227)	26.4% (25.8–27.0)

neighbourhoods with maximal to neighbourhoods with minimal heterogeneity in land uses (i.e., $\text{LUM}_{\text{constant}}=1$ versus $\text{LUM}_{\text{constant}}=0$). The steps counts produced by these models were used to quantify the bias resulting from using $\text{LUM}_{\text{variable}}$ under each of the varying effects.

2.4. Rural/urban location

Point locations were linked to Canadian postal codes in ArcMap 10.1 using the 2009 Platinum Postal Suite Forward Sortation Areas file (DMTI Spatial)™. Rural and urban locations were classified according to the Canada Post classification system where rural locations were defined as postal codes in which the second character was equal to 0 and urban locations were defined as postal codes in which the second character was greater than or equal to 1.

2.5. Statistical analysis

The mean difference between the two measures of land use mix was calculated and the amount of measurement error in the $\text{LUM}_{\text{variable}}$ score was defined as the percentage by which it overestimated the $\text{LUM}_{\text{constant}}$ score. Univariate linear regression models were used to assess the associations between daily steps counts and the two measures of land use mix, overall and by rural location. Measurement bias was calculated as the percentage difference in the parameter estimates between the true and the biased models. All analyses were conducted using SAS 9.2 (SAS 9.2; SAS Institute Inc., Cary, NC, USA). 95% Confidence intervals (CI) were used in the interpretation of results.

3. Results

The average value for $\text{LUM}_{\text{constant}}$ was 0.21 with a standard deviation (SD) of 0.22. This was comparable to the average value for $\text{LUM}_{\text{variable}}$ (0.28, SD = 0.28). Ninety-one per cent (91.1%) of the neighbourhoods were located in urban centres. Zero, one, two, three and four of the land uses of interest were contained in 11.1%, 25.9%, 24.2%, 21.8% and 17.1% of the neighbourhood buffers, respectively.

The mean difference between $\text{LUM}_{\text{variable}}$ and $\text{LUM}_{\text{constant}}$ (0.07, 95% CI −0.11 to 0.07) represented a 32.9% overestimation of the true raw score (95% CI −52.6% to 34.0%). The parameter estimates of the linear models for the two LUM variables and steps/day overall and by rural/urban location are presented in Table 1. Use of the $\text{LUM}_{\text{variable}}$ measure resulted in a systematic underestimation of the true association by 26.4% (95% CI 25.8–27.0%). The underestimation was 7.5% greater in rural compared to urban neighbourhoods.

4. Discussion

While many studies assess land use mix via the Shannon entropy formula (Hess et al., 2001; Leslie et al., 2007; Coffee et al., 2013; Cervero 1997; Duncan et al., 2010; Muller-Riemenschneider et al., 2013), few provide a clear definition of the denominator that is used in the calculation of this score. Given that these studies serve as guides for other researchers and there is evidence that the entropy formula may have been previously misspecified (Frank et al., 2005), it is important to revisit the original formula and encourage its appropriate use. To our knowledge, this is the first study to quantify the bias associated with misspecifying the Shannon entropy formula. We demonstrated that using a variable rather than a constant definition of N systematically underestimated by 26.4% the association between the actual land use mix scores of 9348 Canadian home neighbourhoods and a corresponding simulated dataset of daily step counts. The underestimation was 7.5% greater among rural compared to urban neighbourhoods, suggesting that the bias may be greater in studies of neighbourhoods that contain fewer land use categories.

It is important to note that even when land use mix is calculated correctly, the entropy score only accounts for the proportion of land uses in a given geographical region. As noted by others (Hess et al., 2001; Manaugh and Kreider, 2013), it does not account for the relative importance of different land uses, the interaction between land uses, or the shape configurations of these land uses. For example, a neighbourhood containing 80%

commercial and 20% residential areas would be given the same land use mix score as a neighbourhood containing 80% residential and 20% commercial areas. In theory, however, the former should be given greater weight as it would provide residents with more walking opportunities. In terms of land use interaction, take for example, two neighbourhoods that both contain a 50–50% split between residential and commercial land area. In one neighbourhood, the residential land area may be grouped in half of the neighbourhood and the commercial land area in the other half. In the second neighbourhood, the residential areas may be interspersed throughout the commercial areas. In theory, the latter neighbourhood should be given more weight on the land use mix scale, given that the maximized interaction between the residential and commercial areas would be provide more opportunities for walking than if the two land uses were highly segregated. Manaugh and Kreider (2013) have proposed an interaction measure that captures this level of detail. Lastly, even though certain land area shapes may be more conducive to walking than others, the entropy score does not account for the shapes of the land use areas. For example, a polygon-shaped piece of commercial land would be expected to be more conducive to walking than a circular piece of commercial land of the same area. This may be because a polygon-shaped piece of land would allow for greater interactions with other land uses, but also because a more maze-shaped land area may encourage more exploration of the area. Although this issue may be addressed in part by the interaction measure proposed by Manaugh and Kreider (2013), tools such FRAGSTATS may also be used (McGarigal and Marks, 1994).

Despite the limitations inherent in the Shannon entropy score, it remains the most common method for capturing land use mix in the health geography literature, and, if calculated correctly, is a valuable tool for assessing relative land use mixes within neighbourhoods. Because of this, it is important that researchers who choose to use the score calculate it correctly and in a way that minimizes bias. When interpreting the results of this study, it is important to note that, while $\text{LUM}_{\text{constant}}$ is referred to as the unbiased estimate of land use mix, there are other sources of measurement bias that may affect the accuracy of the measurement (e.g., the quality of the land use data) Brownson et al., 2009; Tim, 1995). Nevertheless, because these biases are not expected to be differential across neighbourhoods, the impact on the effect estimates is expected to be minimal. Strengths of this study included a large sample size and a wide variety of neighbourhoods from across Canada.

In conclusion, land use mix is a component of walkability that is suggested to be associated with lower cardiometabolic risk (Coffee et al., 2013; Muller-Riemenschneider et al., 2013). It is commonly assessed in the health geography literature using a variation of the Shannon entropy formula and studied as a potential predictor of physical activity, the variable believed to mediate the association between land use mix and improved health outcomes. Despite its common use, there is a lack of transparency in the calculation of land use mix. In this study we argue that misspecification of the denominator in the commonly entropy score may systematically bias the associations between land use mix and physical activity towards the null. In order to reduce measurement bias in the estimation of these associations, we encourage researchers who choose to use the Shannon entropy formula, to use a constant value for N and to provide a clear definition of their land use mix calculation in future publications.

Acknowledgements

The authors thank Paul A. Peters for deriving the spatial location data and Patrick Bélisle for his assistance with programming. SH is supported by a Canadian Institutes of Health Research (CIHR) Doctoral Research Award. KD is supported through the Fonds de Recherché Sante Québec-Société Québécoise d'Hypertension Arterielle (SQHA)-Jacques de Champlain Clinician Scientist Award. NR was supported by Fonds de Recherché Santé Québec (FRSQ) Career Award (Chercheurs Boursier Health and Society).

References

Brownson, R.C., Hoehner, C.M., Day, K., Forsyth, A., Sallis, J.F., 2009. Measuring the built environment for physical activity: state of the science. Am. J. Prev. Med. 36 (4 Suppl) (S99–S123 e112).

Cervero, R., 1997. Travel demand and the 3Ds: density, diversity, and design. Transp. Res. 2 (3), 199–219.

Christian, H.E., Bull, F.C., Middleton, N.J., et al., 2011. How important is the land use mix measure in understanding walking behaviour? Results from the RESIDE study. Int. J. Behav. Nutr. Phys. Act. 8, 55.

Coffee, N.T., Howard, N., Paquet, C., Hugo, G., Daniel, M., 2013. Is walkability associated with a lower cardiometabolic risk? Health Place 21, 163–169.

Colley, R.C., Garriguet, D., Janssen, I., Craig, C.L., Clarke, J., Tremblay, M.S., 2011. Physical activity of Canadian adults: accelerometer results from the 2007 to 2009 Canadian Health Measures Survey. Health Rep. 22 (1), 7–14.

Ding, D., Gebel, K., 2012. Built environment, physical activity, and obesity: what have we learned from reviewing the literature? Health Place 18 (1), 100–105.

Duncan, M.J., Winkler, E., Sugiyama, T., et al., 2010. Relationships of land use mix with walking for transport: do land uses and geographical scale matter? J. Urban Health 87 (5), 782–795.

Dwyer, T., Ponsonby, A.L., Ukoumunne, O.C., et al., 2011. Association of change in daily step count over five years with insulin sensitivity and adiposity: population based cohort study. Br. Med. J. 342, c7249.

Feng, J., Glass, T.A., Curriero, F.C., Stewart, W.F., Schwartz, B.S., 2010. The built environment and obesity: a systematic review of the epidemiologic evidence. Health Place 16 (2), 175–190.

Ferdinand, A.O., Sen, B., Rahurkar, S., Engler, S., Menachemi, N., 2012. The relationship between built environments and physical activity: a systematic review. Am. J. Public Health 102 (10), e7–e13.

Frank, L., Sallis, J.F., Conway, T.L., Chapman, J.E., Saelens, B.E., Bachman, W., 2006. Many pathways from land use to health: associations between neighborhood walkability and active transportation, body mass index, and air quality. J. Am. Plan. Assoc. 72 (1), 75–87.

Frank, L.D., Andresen, M.A., Schmid, T.L., 2004. Obesity relationships with community design, physical activity, and time spent in cars. Am. J. Prev. Med. 27 (2), 87–96.

Frank, L.D., Schmid, T.L., Sallis, J.F., Chapman, J., Saelens, B.E., 2005. Linking objectively measured physical activity with objectively measured urban form: findings from SMARTRAQ. Am. J. Prev. Med. 28 (2 Suppl. 2), S117–S125.

Frank, L.D., Saelens, B.E., Powell, K.E., Chapman, J.E., 2007. Stepping towards causation: do built environments or neighborhood and travel preferences explain physical activity, driving, and obesity? Soc. Sci. Med. 65 (9), 1898–1914.

Gilmour, H., 2007. Physically active Canadians. Health Rep. 18 (3), 45–65.

Grasser, G., Van Dyck, D., Titze, S., Stronegger, W., 2013. Objectively measured walkability and active transport and weight-related outcomes in adults: a systematic review. Int. J. Public Health 58 (4), 615–625.

Hajna, S., Dasgupta, K., Halparin, M., Ross, N.A., 2013. Neighborhood walkability: field validation of geographic information system measures. Am. J. Prev. Med. 44 (6), e51–55.

Hess, P.M., Moudon, A.V., Logsdon, M.G., 2001. Measuring land use patterns for transportation research. Transp. Res. Rec.: J. Transp. Research Board 1780, 17–24.

Leslie, E., Coffee, N., Frank, L., Owen, N., Bauman, A., Hugo, G., 2007. Walkability of local communities: using geographic information systems to objectively assess relevant environmental attributes. Health Place 13 (1), 111–122.

Manaugh, K., Kreider, T., 2013. What is mixed use? Presenting an interaction method for measuring land use mix. J. Transp. Land Use 6 (1), 63–72.

Manjoo, P., Joseph, L., Pilote, L., Dasgupta, K., 2010. Sex differences in step count-blood pressure association: a preliminary study in type 2 diabetes. PloS One 5 (11), e14086.

Manjoo, P., Joseph, L., Dasgupta, K., 2012. Abdominal adiposity and daily step counts as determinants of glycemic control in a cohort of patients with type 2 diabetes mellitus. Nutr. Diabetes 2, e25.

Marshall, S.J., Levy, S.S., Tudor-Locke, C.E., et al., 2009. Translating physical activity recommendations into a pedometer-based step goal: 3000 steps in 30 minutes. Am. J. Prev. Med. 36 (5), 410–415.

McCormack, G.R., Shiell, A., 2011. In search of causality: a systematic review of the relationship between the built environment and physical activity among adults. Int. J. Behav. Nutr. Phys. Act. 8, 125.

McGarigal, K., Marks, B.J., 1994. Fragstats: Spatial Pattern Analysis Program for Quantifying Landscape Structure. Forest Science Department, Oregon State University, Corvallis, OR.

Muller-Riemenschneider, F., Pereira, G., Villanueva, K., et al., 2013. Neighborhood walkability and cardiometabolic risk factors in australian adults: an observational study. BMC Public Health 13, 755.

Schneider, P.L., Crouter, S., Bassett, D.R., 2004. Pedometer measures of free-living physical activity: comparison of 13 models. Med. Sci. Sports Exerc 36 (2), 331–335.

Shannon, C.E., 1948. A mathematical theory of communication. Bell Syst. Tech. J. 27, 379–423.

Statistics Canada, 2011. Canadian Health Measures Survey (CHMS) Data User Guide: Cycle 1. Statistics Canada, Ottawa, ON.

Tim, U.S., 1995. The application of GIS in environmental health sciences: opportunities and limitations. Environ. Res. 71, 75–88.

Tudor-Locke, C., Bassett Jr., D.R., 2004. How many steps/day are enough? Preliminary pedometer indices for public health. Sports Med. 34 (1), 1–8.

Tudor-Locke, C., Craig, C.L., Brown, W.J., et al., 2011. How many steps/day are enough? For adults. Int. J. Behav. Nutr. Phys. Act. 8, 79.

CHAPTER SIX│ Manuscript 4

Neighborhood walkability, daily steps, and utilitarian walking in Canadian adults

Samantha Hajna,[1] Nancy A. Ross,[1,2] Lawrence Joseph,[1,3] Sam Harper,[1] Kaberi Dasgupta,[1,3]

BMJ Open, 2015, **5(11):e008964**

[1] Department of Epidemiology, Biostatistics and Occupational Health
McGill University, 1020 Pine Avenue West, Montreal, QC, Canada.

[2] Department of Geography, McGill University
805 Sherbrooke Street West, Montreal, QC, Canada.

[3] Department of Medicine, Division of Clinical Epidemiology
McGill University Health Centre, 687 Pine Avenue West, Montreal, QC, Canada.

PREAMBLE

Now that I identified a need for North American studies to be conducted on the association between GIS-derived neighbourhoods walkability and biosensor-assessed daily steps in adults (*Manuscript 1*, Chapter 3) and tested the walkability measures that I would be using in my substantive studies (*Manuscripts 2* and *3*, Chapters 4 and 5), I was ready to estimate the association between walkability and daily steps in Canadian adults.

In this study (*Manuscript 4*), my specific objective was to estimate the association between neighbourhood walkability and daily steps in a large sample of Canadian adults who participated in Cycle 1 (2007-2009) of the Canadian Health Measures Survey (CHMS). I supplemented my analyses with an additional outcome – utilitarian walking – a subset of total walking that has been shown in previous North American studies to be positively associated with neighbourhood walkability.[61,207,218] Given consistent evidence in the literature that neighbourhood walkability is associated with higher levels of self-reported utilitarian walking (Please refer to Chapter 2), this variable was selected for analyses as an indicator of consistency with previously conducted studies in the field. I hypothesized that the influence of the environment on total walking may be less in North America than what was observed in Europe and Japan (*Manuscript 1*) because 1) preferences for car use are higher[132] and physical activity lower[131] in North America compared to Europe and Japan and 2) there is anecdotal evidence that adults in European and in Asia may place more value on their neighbourhoods in daily living than in North America.

In addition to conducting all of the data analyses and writing this manuscript, I designed this study under the guidance of my supervisors and led the writing of the Social Sciences and Humanities Research Council proposal that was required to analyse these data in the McGill-Concordia Laboratory of the Quebec Interuniversity Centre for Social Statistics (QICSS). I also obtained additional funding for this study through a Quebec Inter-University Centre for Social Statistics Matching Grant. Due to Statistics Canada's strict policies regarding the use of individual-level spatial data, it took me an additional two years to obtain access to the environmental data that I needed for this study. This process involved 1) obtaining a masked dataset of 9,351 latitude/longitude coordinates from across Canada (5,604 of which corresponded to the addresses of the CHMS participants), 2) deriving the built environment variables outside of the QICSS laboratory and 3) sending the file back to Statistics Canada. Statistics Canada then merged my built environment file with the individual-level data collected by the CHMS, removed all of the spatial data, and sent the file to the QICSS laboratory where I could do the analyses that I proposed. I started the process of obtaining these data on September 22, 2011 when I attended the Health Data Users Conference in Ottawa, Canada. The final built environment file was sent to the QICSS Laboratory on September 25, 2013. This manuscript has been published in *BMJ Open* **(Hajna et al., 2015, 5(11):e008964)**. The online supplemental files that are referenced in this manuscript are provided in Appendix E. Although I did not report the individual-level predictors of total walking in this publication, for the interested reader, I have provided a summary of these in Appendix F Please note that during the production process of this manuscript, the numeric component of the formula outlined on page 3 was erroneously superscripted and listed as a reference. The formula should correctly read: “land use mix = (-1) $\Sigma_k(p_k \ln p_k)/\ln N$ where p was the proportion of land area devoted to the specific land use (k) in each buffer divided by ln(4).”

BMJ Open

Neighbourhood walkability, daily steps and utilitarian walking in Canadian adults

Samantha Hajna,[1] Nancy A Ross,[1,2] Lawrence Joseph,[1,2] Sam Harper,[1]
Kaberi Dasgupta[1,3]

To cite: Hajna S, Ross NA, Joseph L, *et al*. Neighbourhood walkability, daily steps and utilitarian walking in Canadian adults. *BMJ Open* 2015;**5**:e008964. doi:10.1136/bmjopen-2015-008964

▸ Prepublication history and additional material is available. To view please visit the journal (http://dx.doi.org/10.1136/bmjopen-2015-008964).

Received 2 June 2015
Revised 31 August 2015
Accepted 28 September 2015

[1]Department of Epidemiology, Biostatistics and Occupational Health, McGill University, Montréal, QC, Canada
[2]Department of Geography, McGill University, Montréal, QC, Canada
[3]Division of Clinical Epidemiology, Department of Medicine, McGill University Health Centre, Montréal, QC, Canada

Correspondence to
Dr Kaberi Dasgupta;
kaberi.dasgupta@mcgill.ca

ABSTRACT

Objectives: To estimate the associations of neighbourhood walkability (based on Geographic Information System (GIS)-derived measures of street connectivity, land use mix, and population density and the Walk Score) with self-reported utilitarian walking and accelerometer-assessed daily steps in Canadian adults.

Design: A cross-sectional analysis of data collected as part of the Canadian Health Measures Survey (2007–2009).

Setting: Home neighbourhoods (500 m polygonal street network buffers around the centroid of the participant's postal code) located in Atlantic Canada, Québec, Ontario, the Prairies and British Columbia.

Participants: 5605 individuals participated in the survey. 3727 adults (≥18 years) completed a computer-assisted interview and attended a mobile clinic assessment. Analyses were based on those who had complete exposure, outcome and covariate data (n=2949).

Main exposure measures: GIS-derived walkability (based on land use mix, street connectivity and population density); Walk Score.

Main outcome measures: Self-reported utilitarian walking; accelerometer-assessed daily steps.

Results: No important relationship was observed between neighbourhood walkability and daily steps. Participants who reported more utilitarian walking, however, accumulated more steps (<1 h/week: 6613 steps/day, 95% CI 6251 to 6975; 1 to 5 h/week: 6768 steps/day, 95% CI 6420 to 7117; ≥6 h/week: 7391 steps/day, 95% CI 6972 to 7811). There was a positive graded association between walkability and odds of walking ≥1 h/week for utilitarian purposes (eg, Q4 vs Q1 of GIS-derived walkability: OR=1.66, 95% CI 1.31 to 2.11; Q3 vs Q1: OR=1.41, 95% CI 1.14 to 1.76; Q2 vs Q1: OR=1.13, 95% CI 0.91 to 1.39) independent of age, sex, body mass index, married/common law status, annual household income, having children in the household, immigrant status, mood disorder, perceived health, ever smoker and season.

Conclusions: Contrary to expectations, living in more walkable Canadian neighbourhoods was not associated with more total walking. Utilitarian walking and daily steps were, however, correlated and walkability demonstrated a positive graded relationship with utilitarian walking.

Strengths and limitations of this study

- This is the first study to estimate the relationship of Geographic Information Systems-derived measures of neighbourhood walkability (ie, street connectivity, land use mix and population density), and the Walk Score with both self-reported utilitarian walking and accelerometer-assessed daily steps in a large sample of Canadian adults.
- Major strengths of this study included a large sample size, assessment of daily steps using accelerometers, consideration of individual and area-level covariates, use of multiple measures of walkability, and the inclusion of a wide variety of neighbourhoods from across Canada.
- Owing to the cross-sectional study design, conclusions regarding causality and the directionality of the associations could not be made.
- The amounts of self-reported utilitarian walking and daily steps that occurred in the home neighbourhood were unknown. Studies on the association between neighbourhood walkability and neighbourhood-specific physical activity are needed.

INTRODUCTION

Sales of passenger cars increased sharply in North America after World War II.[1 2] Before this people had to rely on walking or on public transportation to get from place to place. To facilitate such activity, neighbourhoods were designed to be walkable.[2] People lived in close proximity to services that were required for daily living and their streets were highly connected allowing for easy access to these services.[2] With the advent of the automobile and the US Federal Highway Act of 1956 came a demand for the development of automobile-oriented neighbourhoods.[2–4] The majority of these neighbourhoods contained only residential homes, had long minimally connected street networks and had low population densities compared with prewar neighbourhoods. Owning a car and a home outside of the city was the new American dream.[4] The problem with this new way of living was that people became dependent on their cars to do even the smallest errands.[2] This loss of routine movement is hypothesised to be a contributor to the marked reduction in physical activity that has been observed in North America over the past 70 years.[5 6]

In the hopes of recreating neighbourhoods that are supportive of walking, there is interest in identifying neighbourhood characteristics that are associated with higher levels of walking.[7 8] Three constructs have consistently emerged as key determinants of walking. These include population *density*, *diversity* of destinations and *pedestrian-friendly designs*.[9 10] The variables that best capture design, diversity and density are *street connectivity*, *land use mix* and *residential density* (collectively referred to as neighbourhood walkability).[11 12]

Higher density neighbourhoods with many amenities and well-connected streets have been linked to higher levels of utilitarian walking (ie, walking for specific purposes such as travel to work or school).[13 14] Utilitarian walking is only reasonably collected by self-report and represents a subset of total walking captured by biosensors. Given the potential for biases associated with self-reported measures of physical activity,[15 16] combining self-reported utilitarian walking with objective measures of total physical activity is advantageous. It allows researchers to isolate the policy-amenable subset of total physical activity (utilitarian walking) while also providing estimates of the potential for walkable environments to influence total physical activity.

The association of 'so-called' neighbourhood walkability with total walking—the more salient correlate of improved cardiometabolic health outcomes[17–20]—is less clear. While positive associations have been reported in some studies,[21–23] studies in which researchers use researcher-assessed measures of neighbourhood walkability and/or biosensor-assessed metrics of total physical activity have been less likely to find important associations.[8 24 25] Given that there is a mismatch between perceived and researcher-assessed walkability,[26–28] and that self-reported measures of physical activity may not capture actual levels of physical activity,[16 29] use of researcher-assessed measures of both neighbourhood features and physical activity is preferred when seeking to estimate the association between actual neighbourhood designs and total physical activity.

Numerous studies have been conducted on the association between biosensor-assessed physical activity (eg, minutes spent in moderate-to-vigorous intensity physical activity, MVPA) and Geographic Information System (GIS)-derived measures of street connectivity, land use mix, and population and/or population/residential density.[8 30–32] Only six studies have specifically assessed this association using biosensor-assessed daily steps.[33–38] Daily steps are an outcome of particular interest for the study of neighbourhood walkability for several reasons. First, daily steps provide an accurate estimate of total habitual physical activity.[39 40] Much of this lower intensity activity is not captured by other commonly used biosensor-assessed measures, such as minutes spent in MVPA. Second, walking is the most common and preferred form of physical activity among adults.[40 41] Understanding if neighbourhood walkability is associated with daily steps among adults would suggest that neighbourhood-level interventions may have the potential to impart a benefit to large segments of the population. Third, daily steps are highly interpretable[20] by both scientific and lay communities. This is unlike other biosensor-assessed metrics (eg, accelerometer counts) that may also be good at capturing total levels of physical activity, but are of less value when trying to explain the association of walkability with physical activity in an easily interpretable and relevant way. For example, saying that living in a high compared with a low walkable neighbourhood is associated with x more steps/day is more interpretable and readily understood by the public than saying that it is associated with x more activity counts.

Based on a recent systematic review and meta-analyses of studies that have been done using biosensor-assessed daily steps, we know that in Europe and in Asia, adults who live in high compared to low walkable neighbourhood accumulate 766 more steps/day (95% credible interval: 250, 1271).[42] This accounts for approximately 8% of recommended daily steps. We do not know, however, what this association is like in Canada. Since adults living in Europe and in Asia are more physically active than North American adults[43] and might also have very different opinions regarding the importance of walking-friendly neighbourhoods, the influence of walkability on total physical activity may be different in the Canadian context. The Canadian studies that have been conducted to date have been restricted to a single city with limited variability in neighbourhood walkability and/or relatively small sample sizes.[44–46] A large study (n=151 318) was published on the association of neighbourhood walkability as captured by the publicly available Walk Score with total, utilitarian and leisure-time walking, but the measures of physical activity were based on self-report.[21] Studies with large variability in neighbourhood walkability, a population-based sample of adults, and researcher-assessed exposures and outcomes are needed to elucidate the role of neighbourhood walkability on total physical activity in the general Canadian adult population. This was the first study to estimate the association of researcher-assessed neighbourhood walkability (measured using GIS and the Walk Score) with both self-reported utilitarian walking and biosensor-assessed total walking in a large sample of Canadian adults.

METHODS

Study population

The Canadian Health Measures Survey (CHMS) is a biennial population-based survey that collects data on a representative sample of Canadians. This study used data from cycle 1 (March 2007 to February 2009) of the CHMS. The sampling and recruitment strategy is explained in detail elsewhere.[47] In brief, the CHMS employed a multistage sampling strategy collecting data from 15 sites from five regions across Canada: British Columbia (including the Yukon), the Prairies (Alberta, Manitoba, Saskatchewan and the Northwest Territories), Ontario, Québec and the Atlantic provinces (Newfoundland and Labrador, Prince Edward Island, Nova Scotia and New Brunswick). The number of data collection sites within each region was proportional to the size of the population, with two sites in British Columbia, two sites in the Prairies, six sites in Ontario, four sites in Québec and one site in the Atlantic provinces. Sites had to have a population greater than 10 000 and be accessible to respondents (ie, within 50 km in urban areas and 100 km in rural areas). Using data from the 2006 Canadian Census, all households within the 15 data collection regions were stratified into one of five age groups (6–11, 12–19, 20–39, 40–59 or 60–79 years) using the respondents' age at the time of the census. This ensured that the dwellings in each stratum had a high probability of having at least one occupant in the desired age range. From these strata, a simple random sample of households was selected. Individuals living in Aboriginal communities or institutions or full-time members of the Canadian Forces were not eligible. Of the 8772 households that were contacted and requested to provide information on current household composition, 6106 complied (69.6%). Using the household composition lists obtained from these households, 7483 individuals were requested to participate in the CHMS. In total, 6604 completed the household questionnaire (88.3%). Of these, 5604 also visited the Medical Examination Centre (MEC) for assessments by medical professionals (84.9%).

Access to the data was granted by the Social Sciences and Humanities Research Council of Canada (12-SSH-MCG-3081).[47] Analyses were performed at the McGill-Concordia Quebec Inter-University Center for Social Statistics (QICSS).

Exposure measures

GIS-derived walkability

Home neighbourhoods were approximated using 500 m polygonal buffers around latitude-longitude coordinates that corresponded to the centroid of the participants' home postal codes. In the Canadian context, postal codes are accurate proxies for home addresses with 87.9% and 96.5% of postal codes falling within 200 and 500 m of the street address, respectively.[48] Buffers were defined based on street networks. Streets that were not pedestrian-friendly (eg, highways) were excluded from the creation of the neighbourhood buffers. Five hundred-meter buffers were chosen as the scale of analysis as these approximated a 5–10 min walk from the home and would capture the environment to which the participants are most exposed. Land use mix, street connectivity and population density were calculated for each buffer using ArcMap V.10.1 (ESRI; Redlands, California, USA). *Land use mix* represented the degree of heterogeneity in residential, commercial, institutional/governmental and recreational land uses contained in each neighbourhood buffer. It was calculated using the commonly used entropy formula:[11 49] land use mix=$(-1)\ \Sigma_k(p_k \ln p_k)/\ln N$ where p was the proportion of land area devoted to the specific land use (k) in each buffer divided by ln.[4] (*Note:* p Value was calculated as the land area devoted to a specific land use divided by the total area of walkable land uses.) The score ranged from 0 to 1 where a higher value indicated a greater diversity in land uses. *Street connectivity* was calculated as the number of ≥3-way intersections per square kilometer in each neighbourhood buffer. *Population density* represented the unadjusted census population counts per square kilometer of the dissemination area in which each spatial coordinate fell. Land use mix and street connectivity were based on data obtained from the 2009 DMTI CanMap Streetfiles.[50] Population density was based on the 2006 Canadian Census Population Counts File.[51] Similar to previously used methods,[23 26 52 53] GIS-derived walkability was calculated by summing the z-scores of the three measures. A higher score indicated greater walkability.

Walk Score

The Walk Score is a validated measure of the walkability of a geographic location based on its proximity to 13 walkable destinations.[54–56] The score ranges from 0 (car-dependent) to 100 (walker's paradise), and is calculated based on an algorithm that assigns equal weights to each walkable destination.[57] It is relevant to the construct of walkability as it reflects the diversity and density of neighbourhoods. A higher Walk Score is indicative of a greater diversity of services and also higher population density, which creates a higher demand for such services.[11] Walk Scores were derived in two steps. First, the anonymous spatial coordinates were linked to postal codes using the 2009 Platinum Postal Suite Forward Sortation Areas file.[58] The postal codes were then linked to the Walk Scores using the publicly available interface (http://www.walkscore.com).

Outcome measures

Daily steps

Ambulatory participants wore an accelerometer (Actical; Phillips Respironics, Oregon, USA) during waking hours on their right hip for seven consecutive days. The Actical accelerometer is a small lightweight device that measures acceleration in all directions. The step count function of the Actical has been validated in adults.[59] Accelerometers were initialised to begin data collection at midnight following the MEC assessment. After 7 days, participants mailed the devices to Statistics Canada in postage-paid envelopes. Daily steps equalled the total steps accumulated divided by the number of days for which valid steps were recorded.

Utilitarian walking

Utilitarian walking was ascertained through a question that has been used in previous Canadian national health surveys:[60 61] In a typical week in the past 3 months, how many hours did you usually spend walking to work or to school or while doing errands (None, <1, 1–5, 6–10, 11–20, >20 h)?

Covariates

Age, sex, married/common law status, children ≤15 years in the household, immigrant status, total annual household income ≥$40 000, smoking status, presence of a mood disorder (depression, bipolar disorder, mania or dysthymia) and perceived health (poor, fair, good, very good, excellent) were assessed as part of the computer-assisted interview. A cut-off of ≥$40 000 for total annual household income was selected as it corresponded to the minimum income required to qualify a household with four members as middle class.[62] Body mass index was based on height and weight measurements collected during the mobile clinic assessment. Season was based on the dates of the mobile clinic visits and corresponded to solstice calendar definitions of fall, winter, spring and summer. Rural/urban location was based on Canada Post's classification of rural/urban delivery areas.[63]

Statistical analyses

Descriptive statistics were produced for all variables of interest. Spearman correlation coefficients and scatter plots were used to examine the associations between steps/day, GIS-derived walkability and the Walk Score. Linear regression models were used to estimate mean differences in steps/day across quartiles of walkability. Logistic regression models were used to estimate the odds of walking ≥1 h/week for utilitarian purposes across quartiles of walkability. A cut-off of ≥1 h/week was selected based on the distribution of the data and the cut-offs that have been used in previous studies.[25 64–66] Associations were estimated across quartiles of walkability. To facilitate interpretation of these quartiles, the descriptive characteristics of the neighbourhoods that were included in each quartile were produced. A series of models were fitted—unadjusted, partially adjusted and fully adjusted—for the variables identified a priori as potential confounders and/or predictors of interest. Final models were based on complete case data. The association between steps/day and utilitarian walking was explored graphically and by calculating mean differences in steps/day across categories of self-reported hours/week spent in utilitarian walking (ie, <1, 1–5, ≥6), adjusted for GIS-derived walkability and all of the variables included in the fully adjusted regression models.

The choice of the geographic scale at which neighbourhoods are defined may influence the estimated associations between neighbourhood walkability and walking.[67 68] To address this issue, we conducted sensitivity analyses to assess if varying the sizes and shapes of neighbourhood buffers used in the calculation of the GIS-derived walkability index (ie, 1000 m polygonal buffers; 500 and 1000 m line-based buffers) would meaningfully alter the regression results. We also conducted sensitivity analyses to determine if changing the ≥1 h/week threshold for utilitarian walking to ≥6 h/week would meaningfully alter conclusions. Given that the purpose of this study was not to estimate Canada-wide mean values, all of the analyses were unweighted. Statistical analyses were conducted using SAS V.9.4 (SAS Institute Inc, Cary,North Carolina, USA).

RESULTS

Descriptive statistics

Of the 6604 individuals who participated in cycle 1 of the CHMS, 3727 adults (≥18 years) completed the computer-assisted interview and attended the mobile clinic assessment. Of these, 3586 (96.2%) agreed to wear the accelerometer. Valid step count data were available for 3424 adults (95.5%), with the majority of participants (86.5%) wearing their accelerometers for 7 days. Complete exposure, outcome and covariate data were available for 2949 participants. Participants were on average middle-aged (mean 46.6 years, SD=16.4) and accumulated a mean of 7923 steps/day (SD=3792; table 1).

On average, neighbourhoods had a land use mix of 0.20 (SD=0.23; range: 0–1), 53≥3-way intersections/km^2 (SD=31), 4646 residents/km^2 (SD=24 260) and were 'car-dependent' based on the Walk Score's definition of walkability (mean=46, SD=30). The characteristics of the study neighbourhoods by quartile of GIS-derived neighbourhood walkability are presented in table 2.

Participants with complete covariate data (n=2949) who accumulated more daily steps included higher proportions of married/common law individuals, individuals with good-to-excellent perceived health and individuals with total annual household incomes ≥$40 000, and also included lower proportions of women, immigrants and ever smokers than participants without complete covariate data (n=778; see online supplemental file 1).

There was a graded association between daily steps and self-reported time spent in utilitarian walking, with greater utilitarian walking associated with higher daily steps (figure 1). Participants who reported more utilitarian walking (hours/week) accumulated more steps (<1: 6613 steps/day, 95% CI 6251 to 6975; 1 to 5: 6768 steps/day, 95% CI 6420 to 7117; ≥6: 7391 steps/day, 95% CI 6972 to 7811). Those who reported walking ≥6 h/week walked 623 more steps/day (95% CI 261 to 986) than participants who reported walking 1–5 h/week, and 779 more steps/day (95% CI 399 to 1159) than participants who reported walking <1 h/week. The mean difference between participants who reported walking 1–5 h/week

Table 1 Characteristics of Canadian adults who participated in cycle 1 (2007–2009) of the Canadian Health Measures Survey and on whom complete covariate data were available (N=2949)

	Mean	SD
Age, years	46.6	16.4
Steps/day	7923	3792
Body mass index, kg/m^2	27.3	5.5
	Percent	**N**
Being a woman (vs being a man)	51.4	1515
Married/common law (vs widowed, separated, divorced or single/never married)	65.1	1919
Have children ≤15 years old in household (yes vs no)	35.6	1051
Immigrant (yes vs no)	19.9	587
Mood disorder (yes vs no)	8.3	246
Good/very good/excellent perceived health (vs fair/poor)	90.3	2662
Total annual household income ≥$40 000 (vs <$40 000)	77.7	2291
Ever smoker (vs Never-smoker)	50.5	1488
Fall/winter assessment (vs spring/summer assessment)	48.5	1429
Rural location (vs urban location)	14.4	424
≥1 h/week of utilitarian walking (vs <1 h/week)	63.7	1878
≥6 h/week of utilitarian walking (vs<6 h/week)	17.8	526

for utilitarian purposes and those who reported walking <1 h/week was 155 steps/day (95% CI −138 to 448).

Correlation analyses

GIS-derived walkability and the Walk Score were highly correlated (R=0.82, 95% CI 0.80 to 0.83). Neither walkability measure was correlated with average steps/day (GIS-derived walkability: R=−0.03, 95% CI −0.07 to 0.004; Walk Score: R=−0.03, 95% CI −0.06 to 0.01).

Multivariable models

Daily steps

Point estimates suggested negative associations between neighbourhood walkability and steps/day (eg, highest vs lowest GIS-derived walkability quartile: −234 steps/day, 95% CI −630 to 163; highest vs lowest Walk Score quartile: −232 steps/day, 95% CI −631 to 167), but CIs suggest null associations (table 3). The results were comparable when using variable buffer shapes and sizes (see online supplemental file 2).

Utilitarian walking

Living in the highest compared with the lowest quartile of GIS-derived walkability was associated with a 66% increased odds of walking ≥1 h/week for utilitarian purposes (95% CI 1.31 to 2.11). Living in the highest compared with the lowest Walk Score quartile was associated with twofold increased odds of utilitarian walking (OR=2.00, 95% CI 1.57 to 2.54; table 4). Higher odds of utilitarian walking were also observed for the third quartiles of GIS-derived walkability and the Walk Score compared with the first quartiles, albeit smaller than for the fourth quartiles. No conclusive associations were observed for the second compared with the first quartiles of either of the walkability measures. Similar associations were observed when using 1000 m polygonal network buffers, and 500 and 1000 m line-based buffers for GIS-derived walkability (see online supplemental file 2) and when using a cut-off of ≥6 h/week (see online supplemental file 3).

DISCUSSION

No important associations were observed between walkability and daily steps. A positive graded association was observed between neighbourhood walkability and odds of self-reported utilitarian walking. Participants who reported walking ≥6 h/week walked 623 more steps/day than participants who reported walking 1–5 h/week, and 779 more steps/day than participants who reported walking <1 h/week.

Four previous studies compared the daily steps of adults living in low and high walkable neighbourhoods, using measures similar to ours. Two were conducted in Belgium,[34 35] one in the Czech Republic[36] and one in Japan.[37] In the Czech study,[38] participants living in high compared with low walkable neighbourhoods accumulated 2088 more steps/day (95% CI 440 to 3736). In one of the Belgian studies,[34] participants living in high compared with low walkable neighbourhoods accumulated 1222 more steps/day (95% CI 131 to 2313). Although

Table 2 Characteristics of the study neighbourhoods by quartile of Geographic Information System (GIS)-derived neighbourhood walkability (n=2949)

	Street connectivity Number of ≥3 way intersections/km^2		Land use mix Range: 0–1		Population density Population count/km^2		Walk Score	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Quartile 1	12	13	0.003	0.02	173	452	10	17
Quartile 2	52	13	0.05	0.09	1464	1884	41	18
Quartile 3	64	18	0.25	0.15	3050	3332	57	19
Quartile 4	82	24	0.50	0.16	13 882	47 130	77	18

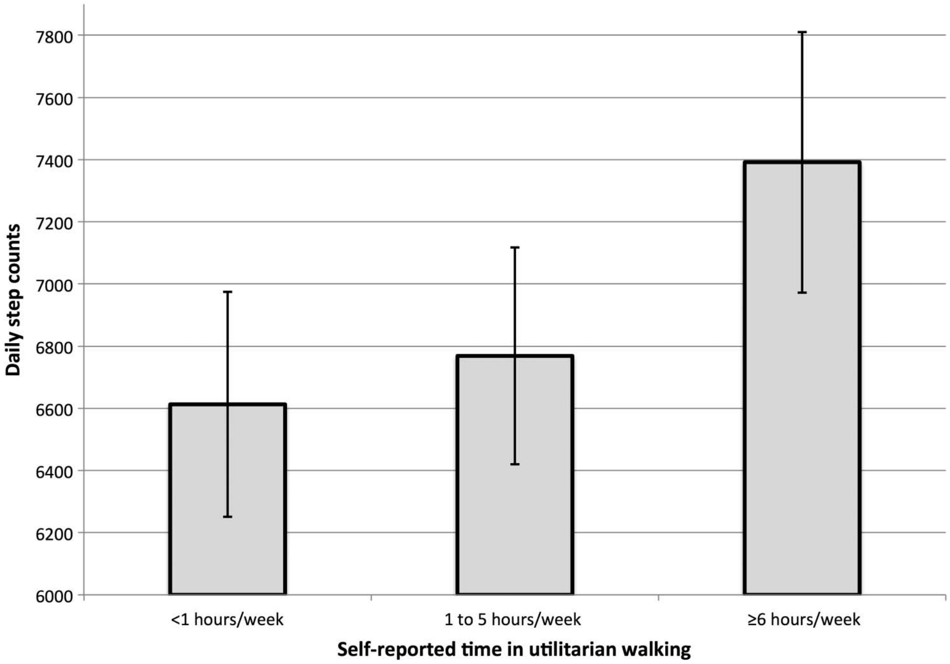


Figure 1 Daily step counts by self-reported time spent in utilitarian walking (n=2949).

the estimates of the other Belgian study[35] and the Japanese study[37] were not conclusive, these also suggested a positive association between walkability and steps. The settings of these studies differ importantly from the Canadian context, possibly accounting for the difference in findings. In contrast to the Czech Republic, Belgium and Japan, there is a heavy reliance on cars in Canada.[69] Neighbourhood walkability, therefore, may not influence travel choices of Canadians sufficiently to affect total steps. While there were no associations between walkability and daily steps when comparing quartiles 3 and 4 to quartile 1 of GIS-derived walkability and when comparing quartile 4 to 1 of the Walk Score, steps were lower in quartile 2 of GIS-derived walkability and quartiles 3 and 2 of the Walk Score when compared with the first quartiles of these measures. This is counter intuitive as it suggests that more walkable neighbourhoods are associated with lower daily steps. This may be a result of quartile 1 being representative of suburban neighbourhoods characterised by good access to public transit. It has been demonstrated that even in very low walkable neighbourhoods, if there are transit stops, residents will walk to board express buses and trains.[70] It may also be a result of the desirable aesthetic or other features in suburban environments that encourage leisure walking.

We identified a positive association of GIS-derived walkability and the Walk Score with self-reported utilitarian walking. This is consistent with prior studies.[16 27–30] Participants (n=1875) in Calgary (Alberta, Canada) living in high compared with low walkable neighbourhoods (based on GIS-derived measures) had a 50% higher odds of walking ≥10 min/week for utilitarian purposes in the last week compared with those who did not (OR=1.50, 95% CI 0.94 to 2.41).[71] In a study of 438 adults living in Ghent Belgium, participants who lived in high compared with low walkable neighbourhoods reported more utilitarian walking (76 min/week vs 16.7 min/week).[72] Similarly, in an analysis of 4552 adults who participated in the Multi-Ethnic Study of Atherosclerosis, every 10-point increase in the Walk Score was associated with 14% higher odds of walking for utilitarian purposes (OR=1.14, 95% CI 1.09 to 1.18).[73]

We were particularly interested in the subgroup of studies that, like ours, concurrently examined the relationship of walkability with utilitarian walking and total walking. The advantage of these studies is that they allow for within-study comparisons of effects. Our findings are consistent with those of American studies conducted on the association between walkability and self-reported utilitarian walking, and total physical activity assessed via self-report or biosensor-assessed metrics.[8 25 74] For example, in a nationally representative sample of 1224 American adults, every 10-point increase in the Walk Score was associated with a 8% higher odds of walking at least 10 min in the past week for utilitarian purposes (OR=1.08, 95% CI 1.01 to 1.14), but no association was observed for total self-reported minutes/week spent walking.[25] Our findings are less consistent with studies conducted in Europe and Asia on the association between GIS-derived walkability and self-reported utilitarian walking and biosensor-assessed daily steps. In two Belgian studies, participants living in high compared with low walkable neighbourhoods engaged 81.5 min/week more (95% CI 66.9 to 96.1)[33] and 75.6 min/week more (95% CI 68.3 to 83.1)[34] in utilitarian walking. No meaningful association was identified between walkability and utilitarian walking in a Japanese study (−4.7 min/day more, 95% CI −10.2 to 0.80).[36] In contrast to our results, three studies signalled positive associations for daily steps (Belgian study: 548 more steps/day, 95% CI −230 to 1326;[34] Belgian study: 1222 more

Table 3 Univariate, partially adjusted and fully adjusted models representing the mean differences in accelerometer-assessed steps/day across quartiles of neighbourhood walkability (n=2949)*,†,‡

	Quartile 2			Quartile 3			Quartile 4			
		95% CI			95% CI			95% CI		
	Steps/day difference	Lower bound	Upper bound	Steps/day difference	Lower bound	Upper bound	Steps/day difference	Lower bound	Upper bound	R^2
GIS-derived walkability										
Model 1	−357	−744	30	−389	−776	−2	−471	−858	−84	0.0023
Model 2	−412	−787	−37	−538	−913	−162	−744	−1121	−367	0.0681
Model 3	−395	−768	−21	−448	−823	−73	−530	−916	−144	0.0865
Model 4	−397	−766	−28	−343	−717	31	−234	−630	163	0.1093
Walk Score										
Model 1	−322	−713	70	−582	−975	−189	−485	−870	−99	0.0033
Model 2	−393	−772	−14	−757	−1137	−376	−772	−1147	−397	0.0698
Model 3	−418	−795	−40	−623	−1005	−242	−555	−941	−169	0.0875
Model 4	−390	−763	−18	−538	−917	−158	−232	−631	167	0.1104

*Quartile 1 (least walkable) served as the reference; GIS-derived walkability index quartiles: <−1.5, ≥1.5, <−0.3, ≥−0.3, <1.1, ≥1.1; Walk Score quartiles: <22, ≥22, <48, ≥48, <68, ≥68.
†Model 1: unadjusted; model 2: adjusted for age, sex and body mass index; model 3: adjusted for age, sex, body mass index, married/common law, income, children, immigrant and mood disorder; model 4: adjusted for age, sex, body mass index, married/common law, income, children, immigrant, mood disorder, perceived health, ever smoker and season.
‡Rural location was not included in the final multivariate models as it was correlated with both GIS-derived walkability and the Walk Score.
GIS, Geographic Information System.

steps/day, 95% CI 131 to 2313;[33] Japanese study: 1070 steps/day, 95% CI −400 to 2540).[36]

Canadians living in more walkable neighbourhoods had higher odds of reporting more utilitarian walking. Although encouraging utilitarian walking may lead to increases in daily steps, we are not able to conclude that walkability is associated with the number of total steps/day that Canadian adults achieve. In interpreting these results, there are some limitations to note. First, some misclassification bias is expected with the use of self-reported utilitarian walking. There are no biosensors, however, that can capture walking purposes, necessitating reliance on self-report. Participants were asked to report their utilitarian walking in the past 3 months and this could mean that the season of assessment (a covariate in fully adjusted models) may not have been time-matched to the self-reported utilitarian walking. However, even if all of the participants at the border of the seasonal categories (fall/winter and spring/summer) reported utilitarian walking based on a different season, assuming up to a 4-week mismatch period that would occur twice every sixth month, only a

Table 4 Odds of ≥1 h/week of utilitarian walking (OR, 95% CI) in univariate, partially adjusted and fully adjusted models across quartiles of neighbourhood walkability (n=2949)*,†,‡

	Quartile 2			Quartile 3			Quartile 4			
		95% CI			95% CI			95% CI		
	OR	Lower bound	Upper bound	OR	Lower bound	Upper bound	OR	Lower bound	Upper bound	Pseudo R^2
GIS-derived walkability										
Model 1	1.19	0.97	1.47	1.64	1.33	2.02	2.19	1.76	2.73	0.0201
Model 2	1.16	0.94	1.42	1.58	1.28	1.96	2.13	1.71	2.66	0.0325
Model 3	1.14	0.92	1.40	1.53	1.23	1.90	1.97	1.57	2.48	0.0358
Model 4	1.13	0.91	1.39	1.41	1.14	1.76	1.66	1.31	2.11	0.0475
Walk Score										
Model 1	1.14	0.93	1.40	1.87	1.51	2.32	2.56	2.06	3.19	0.0318
Model 2	1.11	0.90	1.37	1.85	1.49	2.30	2.50	2.01	3.12	0.0443
Model 3	1.11	0.90	1.37	1.79	1.44	2.24	2.37	1.88	2.98	0.0460
Model 4	1.09	0.88	1.35	1.70	1.36	2.12	2.00	1.57	2.54	0.0555

*Quartile 1 (least walkable) served as the reference; GIS-derived walkability index quartiles: <−1.5, ≥1.5, <−0.3, ≥−0.3, <1.1, ≥1.1; Walk Score quartiles: <22, ≥22, <48, ≥48, <68, ≥68.
†Model 1: unadjusted; model 2: adjusted for age, sex and body mass index; model 3: adjusted for age, sex, body mass index, married/common law, income, children, immigrant and mood disorder; model 4: adjusted for age, sex, body mass index, married/common law, income, children, immigrant, mood disorder, perceived health, ever smoker and season.
‡Rural location was not included in the final multivariate models as it was correlated with both GIS-derived walkability and the Walk Score.
GIS, Geographic Information System.

maximum of 4.7% of participants could have a mismatch between season and utilitarian walking. This is not expected to importantly bias the results of this study. Second, given the cross-sectional nature of this study, conclusions regarding causality and directionality of the associations could not be made and studies evaluating cross-sectional neighbourhood exposures are limited by selection into and out of areas in ways that are likely correlated with the outcomes. Third, two potential confounders (ie, car ownership and residential self-selection[30 53 75–77]) could not be accounted for in our analyses. Fourth, our measures of walking were not context specific. We do not know how much of the reported utilitarian walking and the accumulated number of steps occurred in the home neighbourhood. Studies on the association between neighbourhood walkability and neighbourhood-based physical activity are emerging,[78 79] but these have a high-respondent burden and are not generally feasible for national-scale studies like that presented here. Fifth, there is a possibility of selection bias given minor differences between participants who were included and excluded from the final analyses. Sixth, we focused on the associations of walking with large-scale features of neighbourhood designs. We acknowledge there are other potentially important features of the built environment (eg, aesthetics, neighbourhood safety, presence of crosswalks, transit stops) that may be associated with both utilitarian and/or total walking.[66] Seventh, walking was assessed for up to 7 days, a snapshot that may not be representative of habitual walking levels. If steps were measured over a longer period of time, an association between walkability and daily steps may have emerged. Designing studies where participants are compliant with wearing devices over longer periods of time, however, is difficult.

Despite these limitations, there are several strengths to our study and valuable conclusions that can be drawn. Strengths include a large sample size, biosensor-assessed daily steps, and consideration of individual and area-level covariates (including clinical measures of height and weight). All of these allowed for increased precision in the estimation of associations and minimised the risk of residual confounding. Other strengths include the use of multiple measures of walkability and the inclusion of a wide variety of neighbourhoods from across Canada.

The findings of this study suggest that increasing utilitarian walking may lead to increases in daily steps and that increasing walkability may also lead to increases in utilitarian walking. There was, however, no evidence, that walkability was associated with total daily steps. Given that utilitarian walking is a subcomponent of total daily steps, the important role that walkability may have in increasing utilitarian walking should not be discounted. In Canada, while enhancing walkability may lead to increases in utilitarian walking, other factors will need to be leveraged to promote increases in total walking.

Acknowledgements The analyses presented in this paper were conducted at the Quebec Inter-University Centre for Social Statistics (QICSS), which is part of the Canadian Research Data Centre Network (CRDCN). The services and activities provided by the QICSS are made possible by the financial or in-kind support of the SSHRC, the CIHR, the CFI, Statistics Canada, the FRQSC and the Quebec universities. The authors thank Paul A Peters for deriving the spatial location data, and making these and the environmental data that were derived available for analyses in the McGill-Concordia QICSS. The authors also thank Camille Ouellet Dallaire and Ruilan Shi for their assistance with Geographic Information Systems mapping, and Colin Stewart for retrieving the Walk Score data.

Contributors SH conducted the statistical analyses and wrote the manuscript. SH had full access to the data, and takes responsibility for the integrity of the data and the accuracy of the analysis. KD, NAR and SH developed the study questions. KD and NAR contributed to discussions regarding the analytical methods and to the writing of the manuscript. LJ provided guidance regarding the statistical analyses and reviewed the manuscript for content. All authors contributed to the interpretation of data, reviewed the manuscript for content and approved the final manuscript for submission.

Funding This work was supported by the Canadian Institutes of Health Research (CIHR) through a Doctoral Research Award provided to SH. Support to SH was also provided by a Quebec Inter-University Centre for Social Statistics Matching Grant. KD is supported through a Senior Clinician Scientist Award from the Fonds de Recherché du Québec—Santé (FRQ-S). SH was supported by a FRQ-S Career Award (Chercheurs Boursier Junior 2).

Competing interests None declared.

Ethics approval Health Canada Research Ethics Board.

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement Access to the data was granted by the Social Sciences and Humanities Research Council of Canada (SSHRC). All analyses reported in the study were performed at the McGill-Concordia Quebec Inter-University Center for Social Statistics (QICSS). The data reported in this study are available in an affiliated research data centre to anyone who requests access and are approved by SSHRC/Statistics Canada.

REFERENCES

1. Foster M. *A nation on wheels: the automobile culture in America since 1945*. Belmont, MA: Thomson Learning, 2003.
2. Newman P. Walking in a historical, international and contemporary context. In: Tolley R, ed. *Sustainable trasnport: planning for walking and cycling in urban envionments*. Abington Hall, Abington; Cambridge, England: Woodhead Publishing Limited, 2003:48–58.
3. Speck J. *Walkable city: how downtown can save North America, one step at a time*. New York: Farrar, Straus and Giroux, 2012.
4. Frumkin H, Frank L, Jackson R. *Urban sprawl and public health: designing, planning, and building for healthy communities*. Washington DC: Island Press, 2004.
5. French SA, Story M, Jeffery RW. Environmental influences on eating and physical activity. *Annu Rev Public Health* 2001;22:309–35.
6. Handy SL, Cao X, Mokhtarian PL. Self-selection in the relationship between the built environment and walking. *J Am Plann Assoc* 2006;72:54–74.
7. Handy SL, Boarnet MG, Ewing R, *et al*. How the built environment affects physical activity: views from urban planning. *Am J Prev Med* 2002;23(2 Suppl):64–73.
8. Oakes JM, Forsyth A, Schmitz KH. The effects of neighborhood density and street connectivity on walking behavior: the Twin Cities walking study. *Epidemiol Perspect Innov* 2007;4:16.
9. Cervero R. Travel demand and the 3Ds: density, diversity, and design. *Transpn Res* 1997;2:199–219.
10. Smith KR, Brown BB, Yamada I, *et al*. Walkability and body mass index density, design, and new diversity measures. *Am J Prev Med* 2008;35:237–44.

11. Leslie E, Coffee N, Frank L, *et al*. Walkability of local communities: using geographic information systems to objectively assess relevant environmental attributes. *Health Place* 2007;13:111–22.
12. Saelens BE, Sallis JF, Frank LD. Environmental correlates of walking and cycling: findings from the transportation, urban design, and planning literatures. *Ann Behav Med* 2003;25:80–91.
13. Grasser G, Van Dyck D, Titze S, *et al*. Objectively measured walkability and active transport and weight-related outcomes in adults: a systematic review. *Int J Public Health* 2013;58: 615–25.
14. Saelens BE, Handy SL. Built environment correlates of walking: a review. *Med Sci Sports Exerc* 2008;40(7 Suppl):S550–66.
15. Schmidt MD, Cleland VJ, Thomson RJ, *et al*. A comparison of subjective and objective measures of physical activity and fitness in identifying associations with cardiometabolic risk factors. *Ann Epidemiol* 2008;18:378–86.
16. Lim S, Wyker B, Bartley K, *et al*. Measurement error of self-reported physical activity levels in New York City: assessment and correction. *Am J Epidemiol* 2015;181:648–55.
17. Yates T, Haffner SM, Schulte PJ, *et al*. Association between change in daily ambulatory activity and cardiovascular events in people with impaired glucose tolerance (NAVIGATOR trial): a cohort analysis. *Lancet* 2014;383:1059–66.
18. Gilmour H. Physically active Canadians. *Health Rep* 2007;18:45–65.
19. Tudor-Locke C, Bassett DR, Swartz AM, *et al*. A preliminary study of one year of pedometer self-monitoring. *Ann Behav Med* 2004;28:158–62.
20. Tudor-Locke C, Bassett DR Jr. How many steps/day are enough? Preliminary pedometer indices for public health. *Sports Med* 2004;34:1–8.
21. Thielman J, Rosella L, Copes R, *et al*. Neighborhood walkability: differential associations with self-reported transport walking and leisure-time physical activity in Canadian towns and cities of all sizes. *Prev Med* 2015;77:174–80.
22. Kerr J, Norman G, Millstein R, *et al*. Neighborhood environment and physical activity among older women: findings from the San Diego Cohort of the Women's Health Initiative. *J Phys Act Health* 2014;11:1070–7.
23. Christian HE, Bull FC, Middleton NJ, *et al*. How important is the land use mix measure in understanding walking behaviour? Results from the RESIDE study. *Int J Behav Nutr Phys Act* 2011;8:55.
24. Ferdinand AO, Sen B, Rahurkar S, *et al*. The relationship between built environments and physical activity: a systematic review. *Am J Public Health* 2012;102:e7–13.
25. Tuckel P, Milczarski W. Walk Score (TM), perceived neighborhood walkability, and walking in the US. *Am J Health Behav* 2015;39:242–56.
26. Hajna S, Dasgupta K, Halparin M, *et al*. Neighborhood walkability: field validation of geographic information system measures. *Am J Prev Med* 2013;44:e51–5.
27. McCormack GR, Cerin E, Leslie E, *et al*. Objective versus perceived walking distances to destinations: correspondence and predictive validity. *Environ Behav* 2008;40:401–25.
28. Gebel K, Bauman AE, Sugiyama T, *et al*. Mismatch between perceived and objectively assessed neighborhood walkability attributes: prospective relationships with walking and weight gain. *Health Place* 2011;17:519–24.
29. Garriguet D, Tremblay S, Colley RC. Comparison of Physical Activity Adult Questionnaire results with accelerometer data. *Health Rep* 2015;26:11–17.
30. Ding D, Sallis JF, Norman GJ, *et al*. Neighborhood environment and physical activity among older adults: do the relationships differ by driving status? *J Aging Phys Act* 2014;22:421–31.
31. Saelens BE, Sallis JF, Black JB, *et al*. Neighborhood-based differences in physical activity: an environment scale evaluation. *Am J Public Health* 2003;93:1552–8.
32. De Meester F, Van Dyck D, De Bourdeaudhuij I, *et al*. Active living neighborhoods: is neighborhood walkability a key element for Belgian adolescents? *BMC Public Health* 2012;12:7.
33. Van Dyck D, Deforche B, Cardon G, *et al*. Neighbourhood walkability and its particular importance for adults with a preference for passive transport. *Health Place* 2009;15:496–504.
34. Van Dyck D, Cardon G, Deforche B, *et al*. Urban-rural differences in physical activity in Belgian adults and the importance of psychosocial factors. *J Urban Health* 2011;88:154–67.
35. Dygryn J, Mitas J, Stelzer J. The influence of built environment on walkability using geographic information system. *J Hum Kinetics* 2010;24:93–9.
36. Kondo K, Lee JS, Kawakubo K, *et al*. Association between daily physical activity and neighborhood environments. *Environ Health Prev Med* 2009;14:196–206.
37. Robertson LB, Ward Thompson C, Aspinall P, *et al*. The influence of the local neighbourhood environment on walking levels during the Walking for Wellbeing in the West pedometer-based community intervention. *J Environ Public Health* 2012;2012:974786.
38. Zhang Y, Ning LD, Xin L. Relationship between built environment, physical activity, adiposity and health in adults aged 46–80 in Shanghai, China. *J Phys Act Health* 2015;12:569–78.
39. Tudor-Locke CE, Bell RC, Myers AM, *et al*. Pedometer-determined ambulatory activity in individuals with type 2 diabetes. *Diabetes Res Clin Pract*. 2002;55(3):191–199.
40. Schneider PL, Crouter S, Bassett DR. Pedometer measures of free-living physical activity: comparison of 13 models. *Med Sci Sports Exerc*. 2004;36:331–5.
41. Gilmour H. Physically active Canadians. *Health Reports*. 2007;18:45–65.
42. Hajna S, Ross NA, Brazeau AS, *et al*. Associations between neighbourhood walkability and daily steps in adults: a systematic review and meta-analysis. *BMC Public Health*. 2015;15:768.
43. World Health Organization. *Global health observatory: prevalence of insufficient physical activity*. Geneva, Switzerland: World Health Organization, 2015. http://www.who.int/gho/ncd/risk_factors/physical_activity_text/en/index.html (cited 17 February 2015).
44. McCormack GR, Shiell A, Doyle-Baker PK, *et al*. Subpopulation differences in the association between neighborhood urban form and neighborhood-based physical activity. *Health Place* 2014;28:109–15.
45. Riley DL, Mark AE, Kristjansson E, *et al*. Neighbourhood walkability and physical activity among family members of people with heart disease who participated in a randomized controlled trial of a behavioural risk reduction intervention. *Health Place* 2013;21:148–55.
46. Prince SA, Kristjansson EA, Russell K, *et al*. Relationships between neighborhoods, physical activity, and obesity: a multilevel analysis of a large Canadian city. *Obesity (Silver Spring)* 2012;20:2093–100.
47. Statistics Canada. Canadian Health Measures Survey (CHMS) Data User Guide: Cycle 1 2011; http://www23.statcan.gc.ca/imdb-bmdi/document/5071_D2_T1_V1-eng.htm
48. Bow CJ, Waters NM, Faris PD, *et al*. Accuracy of city postal code coordinates as a proxy for location of residence. *Int J Health Geogr* 2004;3:5.
49. Hajna S, Dasgupta K, Joseph L, *et al*. A call for caution and transparency in the calculation of land use mix: measurement bias in the estimation of associations between land use mix and physical activity. *Health Place* 2014;29:79–83.
50. DMTI Spatial Inc. *CanMap Streetfiles. v2009.3*. Markham, Ontario: DMTI Spatial Inc., 2009.
51. Statistics Canada. *Unadjusted 2006 Canadian Census Population Counts File*. Census Ottawa: Statistics Canada, 2006.
52. Frank LD, Schmid TL, Sallis JF, *et al*. Linking objectively measured physical activity with objectively measured urban form: findings from SMARTRAQ. *Am J Prev Med* 2005;28(2 Suppl 2):117–25.
53. Frank LD, Saelens BE, Powell KE, *et al*. Stepping towards causation: do built environments or neighborhood and travel preferences explain physical activity, driving, and obesity? *Soc Sci Med* 2007;65:1898–914.
54. Carr LJ, Dunsiger SI, Marcus BH. Validation of Walk Score for estimating access to walkable amenities. *Br J Sports Med* 2011;45:1144–8.
55. Carr LJ, Dunsiger SI, Marcus BH. Walk score as a global estimate of neighborhood walkability. *Am J Prev Med* 2010;39:460–3.
56. Duncan DT. What's your Walk Score(R)?: web-based neighborhood walkability assessment for health promotion and disease prevention. *Am J Prev Med* 2013;45:244–5.
57. Carr LJ, Dunsiger SI, Marcus BH. Walk Score™ as a global estimate of neighborhood walkability. *Am J Prev Med* 2010;39:460–3.
58. DMTI Spatial Inc. Platinum Postal Suite: CanMap Forward Sortation Area Boundaries. [computer file]. Markham, 2009.
59. Esliger DW, Probert A, Connor Gorber S, *et al*. Validity of the Actical accelerometer step-count function. *Med Sci Sports Exerc* 2007;39:1200–4.
60. Government of Canada. *Aboriginal Peoples Survey, 2006: an overview of the health of the Métis population*. Statistics Canada, 2006.
61. Government of Canada. *National Population Health Survey: Household Component—Longitudinal Cycle 9 (2010–2011)—Questionnaire*. Ottawa: Statistics Canada, 2009.
62. McMahon T. Who belongs to Canada's middle class? Macleans. 2014. (cited 19 August 2015). http://www.macleans.ca/economy/who-belongs-to-canadas-middle-class/
63. Statistics Canada. *How postal codes map to geographic areas*. Geography Working Paper Series, 2007.

64. Rodríguez DA, Evenson KR, Diez Roux AV, *et al*. Land use, residential density, and walking. The multi-ethnic study of atherosclerosis. *Am J Prev Med* 2009;37:397–404.
65. Knuiman MW, Christian HE, Divitini ML, *et al*. A longitudinal analysis of the influence of the neighborhood built environment on walking for transportation: the RESIDE study. *Am J Epidemiol* 2014;180:453–61.
66. Doescher MP, Lee C, Berke EM, *et al*. The built environment and utilitarian walking in small U.S. towns. *Prev Med* 2014;69: 80–6.
67. Learnihan V, Van Niel KP, Giles-Corti B, *et al*. Effect of scale on the links between walking and urban design. *Geogr Res* 2011;49:183–91.
68. Oliver LN, Schuurman N, Hall AW. Comparing circular and network buffers to examine the influence of land use on walking for leisure and errands. *Int J Health Geogr* 2007;6:41.
69. The World Bank Group. Data: motor vehicles (per 1,000 people). World Development Indicators, International Road Federation, World Road Statistics and Data Files. 2008; 2015 (February 17).
70. Wasfi RA, Ross NA, El-Geneidy AM. Achieving recommended daily physical activity levels through commuting by public transportation: unpacking individual and contextual influences. *Health Place* 2013;23:18–25.
71. Jack E, McCormack GR. The associations between objectively-determined and self-reported urban form characteristics and neighborhood-based walking in adults. *Int J Behav Nutr Phys Act* 2014;11:71.
72. Van Holle V, Van Cauwenberg J, Van Dyck D, *et al*. Relationship between neighborhood walkability and older adults' physical activity: results from the Belgian Environmental Physical Activity Study in Seniors (BEPAS Seniors). *Int J Behav Nutr Phys Act* 2014;11:110.
73. Hirsch JA, Moore KA, Evenson KR, *et al*. Walk Score(R) and Transit Score(R) and walking in the multi-ethnic study of atherosclerosis. *Am J Prev Med* 2013;45:158–66.
74. Norman GJ, Carlson JA, O'Mara S, *et al*. Neighborhood preference, walkability and walking in overweight/obese men. *Am J Health Behav* 2013;37:277–82.
75. Zander A, Rissel C, Rogers K, *et al*. Active travel to work in NSW: trends over time and the effect of social advantage. *Health Promot J Austr* 2014;25:167–73.
76. McCormack GR, Shiell A. In search of causality: a systematic review of the relationship between the built environment and physical activity among adults. *Int J Behav Nutr Phys Act* 2011;8:125.
77. Boone-Heinonen J, Gordon-Larsen P, Guilkey DK, *et al*. Environment and physical activity dynamics: the role of residential self-selection. *Psychol Sport Exerc* 2011;12:54–60.
78. Troped PJ, Wilson JS, Matthews CE, *et al*. The built environment and location-based physical activity. *Am J Prev Med* 2010;38:429–38.
79. Rodriguez DA, Brown AL, Troped PJ. Portable global positioning units to complement accelerometry-based physical activity monitors. *Med Sci Sports Exerc* 2005;37(11 Suppl):S572–81.

CHAPTER SEVEN | Manuscript 5

Neighbourhood walkability and daily steps in adults with type 2 diabetes

Samantha Hajna,[1] Nancy A. Ross,[1,2] Lawrence Joseph,[1,3] Sam Harper,[1] Kaberi Dasgupta,[1,3]

PLoS One, In Press. doi: 10.1371/journal.pone.0151544

[1] Department of Epidemiology, Biostatistics and Occupational Health,
McGill University, 1020 Pine Avenue West, Montreal, QC, Canada.

[2] Department of Geography, McGill University,
805 Sherbrooke Street West, Montreal, QC, Canada.

[3] Department of Medicine, Division of Clinical Epidemiology,
McGill University Health Centre, 687 Pine Avenue West, Montreal, QC, Canada.

PREAMBLE

In my first substantive piece that I presented Chapter 6 (*Manuscript 4*), I determined that there were no important associations between neighbourhood walkability and accelerometer-assessed daily steps in a large cohort of Canadian adults who participated in Cycle 1 (2007-2009) of the Canadian Health Measures Survey. I did, however, find that living in a more walkable neighbourhood was associated with higher odds of self-reported utilitarian walking (i.e., 66% increased odds of walking ≥1 hour/week when living in the most compared to the least walkable neighbourhood (OR: 1.66, 95% CI 1.31, 2.11)). In my next study (*Manuscript 5*), I investigated the association between neighbourhood walkability and daily steps in a clinical sample of adults with type 2 diabetes.

Adults with type 2 diabetes represent a population that is highly inactive and at two to four-fold increased risk for vascular events and premature mortality compared to the general adult population.[96-100] The daily steps of adults with type 2 diabetes fall in low active category (5,000 to 7,499 steps per day) according to the cut-offs proposed by Tudor-Locke[23,99,219-221] placing them well below the recommended level of 10,000 steps or more per day.[222] Facilitating even small increases in walking may have large benefits. In addition to being highly inactive[23,99,219,221] and at increased risk of adverse health outcomes compared to the general adult population,[95] adults with type 2 diabetes are particularly unmotivated to engage in physical activity and face a unique set of barriers to engaging in regular physical activity (e.g., lack of support, shyness, feeling uncomfortable).[133-135] Because of this, it is possible that adults with type 2 diabetes may be particularly sensitive to features of the built environments.[23] In this study I was interested in understanding the association between neighbourhood walkability and total walking among adults with type 2 diabetes. This study has been accepted for publication in ***PLoS One*** **(In Press, doi: 10.1371/journal.pone.0151544)**. *Please note:* Formatting has been retained as per *PLoS One* submission guidelines.

Abstract

Introduction

There is evidence that greater neighbourhood walkability (i.e., neighbourhoods with more amenities and well-connected streets) is associated with higher levels of total walking in Europe and in Asia, but it remains unclear if this association holds in the Canadian context and in chronic disease populations. We examined the relationships of different walkability measures to biosensor-assessed total walking (i.e., steps/day) in adults with type 2 diabetes living in Montreal (QC, Canada).

Materials and Methods

Participants (60.5±10.4 years; 48.1% women) were recruited through McGill University-affiliated clinics (June 2006 to May 2008). Steps/day were assessed once per season for one year with pedometers. Neighbourhood walkability was evaluated through participant reports, in-field audits, Geographic Information Systems (GIS)-derived measures, and the Walk Score®. Relationships between walkability and daily steps were estimated using Bayesian longitudinal hierarchical linear regression models (n=131).

Results

Participants who reported living in the most compared to the least walkable neighbourhoods completed 1345 more steps/day (95% Credible Interval: 718, 1976; Quartiles 4 versus 1). Those living in the most compared to the least walkable neighbourhoods (based on GIS-derived

walkability) completed 606 more steps per day (95% CrI: 8, 1203). No statistically significant associations with steps were observed for audit-assessed walkability or the Walk Score®.

Conclusions

Adults with type 2 diabetes who perceived their neighbourhoods as more walkable accumulated more daily steps. This suggests that knowledge of local neighborhood features that enhance walking is a meaningful predictor of higher levels of walking and an important component of neighbourhood walkability.

Introduction

Higher neighbourhood walkability (i.e., the ‘walking friendliness’ of a neighbourhood) has been linked to higher levels of biosensor-assessed total walking in Europe and in Asia [1], but there is evidence that this association may be null in the Canadian context [2]. Since adults living with chronic diseases face a unique set of challenges to engaging in physical activity, they may be particularly sensitive to features of their neighbourhood environments [3, 4]. Adults with type 2 diabetes are a group of individuals who are particularly inactive and unmotivated to engage in physical activity [5-13]. Several studies have demonstrated positive associations between neighbourhood walkability and physical activity in this population [4, 5, 14], but to our knowledge, no studies have been conducted in North America using biosensor-assessed measures of total walking. From a socio-ecological perspective, it is important to understand the influence of the environment on walking levels in this high-risk, sedentary group of individuals.

Neighbourhood walkability can be assessed using participant-reported (i.e., perceived) measures of walkability, in-field or virtual street-level audits (e.g., Google Street View), and publicly available measures (e.g., Walk Score®). Geographic Information Systems (GIS) - digital methods for processing large amounts of spatial data [15] – represents one of the most common ways that neighbourhood walkability is assessed for research purposes. Using GIS, walkability is often operationalized based on a neighbourhood’s street connectivity, residential and/or population density, and land use mix. Street connectivity is commonly defined as the number of intersections within a given area. More intersections facilitate movement between origins and destinations [16, 17]. Residential and/or population density are defined as the number of people and/or residences within a given area [18]. Areas with greater residential/population densities are generally more conducive to non-motorized transport as a result of there being more people to visit and a greater demand for accessible community services, such as shops and parks [16]. Land use mix is a measure of the evenness of the distribution of the land uses within a neighbourhood [17, 19]. The more types of land uses that are contained within a neighbourhood, the more convenient it is to walk to services supplied by these areas [20, 21].

We previously demonstrated a strong correlation between GIS-derived walkability (based on street connectivity, residential density and land use mix) and an overall index of neighbourhood walkability as captured by an in-field audit [22]. Neither of these measures, however, correlated well with participant-reported walkability [22]. In the present follow-up analysis, we examined the relationships of these three walkability measures to daily steps in a sample of adults living with type 2 diabetes (QC, Canada) on whom we had repeated-measures of pedometer-assessed walking over a one-year period. To our knowledge, no previous study has concurrently examined the relationships of these different walkability measures with daily steps. The objective of this study was to improve our understanding of how neighbourhood environments might influence the physical behaviours of adults living with type 2 diabetes.

We were specifically interested in the association between neighbourhood walkability and daily steps, as opposed to other forms of physical activity (e.g., moderate-to-vigorous intensity physical activity (MVPA)) for two reasons. First, pedometer-assessed daily steps are an accurate measure of total habitual walking in adults [23-25] that have been linked to important health benefits in adults with type 2 diabetes. For example, in a sample of over 9,000 adults with impaired glucose tolerance), pedometer-assessed steps at baseline ((Hazard Ratio) HR for a 2,000 steps/day increment=0.90, 95% CI 0.84, 0.96) and change in steps over an average follow-up of six years (HR per 2000 steps/day increase = 0.92, 95% CI 0.86, 0.99) led to reductions in cardiovascular disease events, (i.e., cardiovascular mortality, stroke, or myocardial infarction)

[26]. Second, since walking is the most common and preferred form of physical activity among adults [27-30], understanding its link to neighbourhood walkability, as opposed to other forms of physical activity, may have population-wide benefits.

Materials and Methods

Study Population

Adults (n=201) with physician-diagnosed type 2 diabetes were recruited through McGill-affiliated outpatient clinics (Montreal, QC) and local diabetes associations between June 2006 and May 2008. They attended four in-clinic assessments, one per season, over the course of one year [31]. As previously described [31, 32], to allow for accurate measurements of steps using pedometers, participants were required to have a normal gait and a body mass index (BMI) of less than 40 kg/m^2. Those who were pregnant or planning a pregnancy were ineligible, as were those with chronic conditions that could compromise glycemic control. Procedures were approved by McGill University’s Faculty of Medicine Institutional Review Board and all participating institutions. Participants provided written informed consent. Written informed consent was recorded using a consent form and procedure that was approved by McGill University's Faculty of Medicine Institutional Review Board.

Measures

Daily Steps

Daily steps were assessed once per season for 14 consecutive days using Yamax SW-701 pedometers with viewing windows concealed [33]. A pedometer with the same step counting mechanism (i.e., the SW-701 model) has been shown to count steps to within 3% of actual steps taken [25, 31, 33]. Participants were provided with three pedometers: A and B were each worn for a seven-day period; C remained in the postage-paid envelope and accounted for extra steps accumulated during the mailing process. Mean daily steps were calculated by dividing the total number of steps accumulated on Pedometers A and B (corrected for the steps accumulated on Pedometer C) by the total number of days the pedometers were worn. In the event that some participants would not be able to wear their pedometers for the full 14-day period, we provided all participants with a form on which they could indicate their wear days.

Participant-reported walkability

Three surveys of social and physical environments have been shown to have good test-retest reliability [31, 34]. In our study questionnaire, we included the items from these surveys that were relevant to our outcome of interest (i.e., walking). The items that we queried included presence/condition of sidewalks, street lighting, traffic, proximity to stores and transit stops, presence of interesting sights, activity level of neighbours, and safety while walking. Based upon the participants' responses to these items, we calculated participant-reported walkability as the sum of the regression-based scores calculated for the factors that we identified via a principal component analysis [35]. A higher score indicated greater walkability.

GIS-derived walkability

Residential neighbourhoods were defined as 500-meter polygonal street network buffers around the centroid of each participant's home postal code address. Street connectivity, residential density and land use mix were calculated within these neighbourhoods using GIS (ArcGIS 10.1;

ESRI; Redlands, CA). Street connectivity was measured as the number of ≥4-way intersections per square kilometer. Residential density was equivalent to the number of residences per square kilometer of residential land area. Land use mix represented the degree of heterogeneity in residential, commercial, institutional and recreational land uses and was equal to (-1) x [((proportion of residential land) ln (proportion of residential land)) + ((proportion of commercial land) ln (proportion of commercial land)) + ((proportion of institutional land) ln (proportion of institutional land)) + ((proportion of recreational land) ln (proportion of recreational land))] / ln 4. The land use mix score ranged from 0 to 1. A higher score indicated a greater mixing of land uses within a neighbourhood. Land use mix and street connectivity were calculated based on data obtained from the 2008 DMTI Quebec land use and Montreal road segment files [36, 37]. Residential density was calculated using data obtained from 2006 Canadian Census files [38]. In line with previous methods [17, 19, 35, 39], GIS-derived walkability was calculated by summing the z-scores of street connectivity, residential density and land use mix. A higher score indicated greater overall neighbourhood walkability based on these three measures. We have previously validated this measure in this study population against neighbourhood walkability assessed via the in-field audit that we describe below (R=0.7, 95% CI 0.6, 0.8) [22].

Audit-assessed walkability

Five randomly-selected street segments within 500-meters of each participant's home postal code were audited in 2009 using a 21-item modified version of the Pedestrian Environment Data Scan (PEDS) [40]. PEDS has been shown to be a reliable tool for the assessment of pedestrian environments [40]. Audit-assessed walkability was quantified as the sum of the regression-based scores calculated for the factors identified via a principal component analysis [22]. A higher score indicated greater walkability.

Walk Score®

The Walk Score® is a validated measure that captures the walkability of a geographic location based on its proximity to 13 walkable destinations (e.g., stores) using a publicly available interface (www.walkscore.com) [41, 42]. The score ranges from 0 (car-dependent) to 100 (walker's paradise) and is calculated based on an algorithm that assigns equal weights to each of the walkable destinations [41, 42].

Covariates

Age, sex, insulin use, annual household income (≥\$50,000), married/common-law, university education, ethnicity, immigrant status, smoking status, dog ownership, and diabetes duration were reported by participants at baseline. BMI was computed from direct weight and height measurements taken at baseline. Depressed mood was assessed at each visit using the Center for Epidemiologic Studies-Depression Scale (CES-D Score ≥16) [43, 44]. Residential self-selection (11-items from the Neighbourhood Quality of Life Study questionnaire [45]), vehicle access, years living at address, and past participation in regular physical activity were ascertained as part of a follow-up survey mailed to participants in the winter of 2012/2013. Season was based on visit date and corresponded to solstice calendar definitions of fall, winter, spring and summer (e.g., fall: September 22/23 to December 20/21). Because steps were similar in the spring and summer and in the fall and winter [32], seasons were dichotomized into spring/summer and fall/winter categories.

Statistical analysis

Descriptive statistics were produced for all variables of interest overall and by quartile of GIS-derived neighbourhood walkability. Spearman correlation coefficients and scatter plots were produced for the associations between steps, participant-reported walkability, GIS-derived walkability, audit-assessed walkability and the Walk Score®. Given repeated (seasonal) measures of steps, Bayesian hierarchical linear regression models with diffuse priors were used to estimate the associations between the measures of walkability (across quartiles) and steps over time (WinBUGS 1.4.3). Associations between season and steps were assessed at concurrent time points. Data on residential self-selection, vehicle access, years living at address, and past participation in physical activity were available on only a subgroup of participants who completed the follow-up survey (n=78). Because of the influence on sample size and the fact that adjustment for these variables did not appear to lead to important changes to the main estimates of interest (i.e., walkability and daily steps), we did not include them in the final models. Final models were based on complete case data (n=131). Variables were selected into the models based on theoretical importance and/or if they were identified (based on univariate and correlation analyses) as potential confounders or predictors of daily steps. The interpretation of findings was based on 95% credible intervals (CrI), the Bayesian analog of frequentist confidence intervals (CI). All analyses were conducted in 2014.

Results

Descriptive statistics

Sixty-nine percent (69.2%) of participants attended all four visits with over 84.1% attending three visits. Of the 688 visits attended, 182 occurred in spring (26.5%), 165 in summer (24.0%), 185 in fall (26.9%), and 156 in winter (22.7%). 174 participants (86.6%) were evaluated at least once during both the spring/summer and the fall/winter periods. Of the 201 participants enrolled, 108 participants returned the mailed questionnaire. Of these, 78 (38.8%) provided complete data on all four additional covariates of interest, including residential self-selection, vehicle access, years living at address, and past physical activity.

Participants (mean=60.5 years, standard deviation (SD)=10.4) averaged 5388 steps/day (SD=2488). The most walkable neighbourhoods (i.e., Quartile 4) had the lowest proportion of married couples, people having annual household incomes of more than $50,000 per year, and people with regular access to a vehicle (Table 1). A negative graded association was observed between neighbourhood walkability and regular vehicle access with those living in less walkable neighbourhoods, having greater regular access to a vehicle (Q1: 92.9%; Q2: 88.9%; Q3: 86.7%; Q4: 55.0%). The most walkable neighbourhoods contained the highest proportion of immigrants (Table 1). There was no discernable pattern in daily steps across quartiles of neighbourhood walkability (Table 1). On average, neighbourhoods were “somewhat walkable” based on the Walk Score® definition of walkability (Walk Score®=69, SD=19). There was good variability in neighbourhood walkability as assessed by the Walk Score® with 17.5% of the study population living in “car dependent” neighbourhoods (i.e., Walk Scores®<49) and 12.2% of the study population living in “very walkable/Walker’s paradise” neighbourhoods (Table 2). Some differences were observed between completers and non-completers of the follow-up survey (e.g., more women and university educated adults completed the follow-up survey, S1 Table, Appendix G) and between participants included and excluded from the final models (e.g., more women and adults earning ≥$50,000 per year were included in the final models, S2 Table, Appendix G).

Table 1. Characteristics of the study population at baseline by quartile of neighbourhood walkability (n=131).[a,b]

		Neighbourhood walkability[a]			
	Overall[b]	**Quartile 1**	**Quartile 2**	**Quartile 3**	**Quartile 4**
	mean (SD)	**mean (SD)**	**mean (SD)**	**mean (SD)**	**mean (SD)**
Age, *years*	60.5 (10.4)	60.8 (9.5)	63.0 (9.8)	58.9 (11.9)	59.2 (10.0)
Body mass index, kg/m^2	30.3 (5.8)	30.4 (6.1)	29.0 (5.9)	31.6 (5.3)	30.1 (5.8)
Daily steps	5388 (2488)	5121 (2593)	5828 (2462)	4816 (2468)	5764 (2397)
Walk Score®	69 (19)	48 (15)	64 (15)	79 (10)	84 (12)
	%	**%**	**%**	**%**	**%**
Women	48.1	37.5	21.2	68.8	35.3
Married/common-law	69.5	87.5	78.8	56.3	55.9
University education	38.2	40.6	42.4	13.3	38.2
Annual household income, *≥$50,000*	45.3	60.7	57.1	34.5	31.3
Ethnicity, *White*	71.0	68.8	69.7	75.0	70.6
Immigrant	45.0	43.8	42.4	37.5	55.9
Depressed mood	28.2	28.1	12.2	37.5	35.3
Dog ownership	14.5	21.9	6.1	18.8	11.8
Insulin use	34.4	40.6	36.4	40.6	20.6
Regular vehicle access	79.1	92.9	88.9	86.7	55.0
Past regular exercise	80.6	78.6	83.3	93.3	70.0

[a] Quartile cut-offs for the GIS-derived walkability index: Quartile 1: < -2.17 (n=32); Quartile 2: ≥-2.17<0.13 (n=33); Quartile 3: ≥0.13<1.67 (n=32); Quartile 4: ≥1.67 (n=34); Q1: annual household income (n=28), regular vehicle access and past regular exercise (n=14); Q2: daily steps (n=32), annual household income (n=28), regular vehicle access and past regular exercise (n=18); Q3: Annual household income (n=29), regular vehicle access and past regular exercise (n=15); Q4: Annual household income (n=32), regular vehicle access and past regular exercise (n=20).

[b] Daily steps (n=130); annual household income (n=117); regular vehicle access and past regular exercise (n=67).

Table 2. The distribution of neighbourhood walkability (based on the Walk Score®)[a] in the study population (n=131).

Walk Score®	**Walk Score Category®**	**% (n)**
90-100	Walker's Paradise *(Daily errands do not require a car)*	12.2% (16)
70-89	Very Walkable *(Most errands can be accomplished on foot)*	45.0% (59)
50-69	Somewhat walkable *(Some errands can be accomplished on foot)*	25.2% (33)
25-49	Car-dependent *(Most errands require a car)*	16.0% (21)
0-24	Car-dependent *(Almost all errands require a car)*	1.5% (2)

[a] Categories and descriptions are taken directly from www.walkscore.com

Correlation Analyses

The Walk Score® correlated moderately with audit-assessed walkability (R=0.5, 95% CI 0.3, 0.6; n=201) and GIS-derived walkability (R=0.8, 95% CI 0.7, 0.8; n=200) and minimally with participant-reported walkability (R=0.1, 95% CI -0.01, 0.3; n=200). The correlations among the other measures have been reported previously (audit/GIS: R=0.7, 95% CI 0.6, 0.8; participant-reported/audit: R=0.2, 95% CI 0.1, 0.3; participant-reported/GIS: R=0.2, 95% CI 0.04, 0.3) [22]. Scatter plots between the four walkability measures and steps are provided in S1 and S2 Figs (Appendix G). A small correlation was observed between steps and participant-reported walkability (R=0.2, 95% CI 0.1, 0.3; n=194, S2 Fig a, Appendix G). There was very little relation between steps and the other walkability measures (S2 Fig b-d, Appendix G).

Multivariate models

Participant-reported walkability

Adults who reported living in the most compared to the least walkable neighbourhoods completed 1345 more steps/day (95% CrI: 718, 1976). There were no important differences for the first through third quartiles (Table 3).

Table 3. Mean differences in daily steps across quartiles of each of the measures of neighbourhood walkability (n=131).

	Increment in Daily Steps (95% credible interval)[a,b]		
	Quartile 2	**Quartile 3**	**Quartile 4**
Participant-reported walkability	*mean=-0.4, SD=0.4*	*mean=0.7, SD=0.2*	*mean=1.9, SD=0.7*
Model 1	34 (-1050, 1103)	-393 (-1545, 768)	1344 (88, 2572)
Model 2	122 (-440, 688)	-189 (-774, 408)	1364 (733, 1990)
Model 3	103 (-457, 677)	-197 (-774, 395)	1345 (718, 1976)
	Quartile 2	**Quartile 3**	**Quartile 4**
GIS-derived walkability	*mean=-0.9, SD=0.7*	*mean=1.0, SD=0.5*	*mean=3.0, SD=1.2*
Model 1	970 (-188, 2133)	143 (-990, 1276)	794 (-354, 1976)
Model 2	1011 (412, 1604)	57 (-550, 653)	724 (130, 1314)
Model 3	783 (168, 1406)	-30 (-616, 557)	606 (8, 1203)
	Quartile 2	**Quartile 3**	**Quartile 4**
Audit-assessed walkability	*mean=-0.6, SD=0.3*	*mean=0.5, SD=0.4*	*mean=2.5, SD=1.3*
Model 1	-214 (-1364, 941)	-279 (-1441, 899)	-410 (-1608, 811)
Model 2	-325 (-916, 264)	119 (-481, 713)	-87 (-699, 507)
Model 3	-157 (-753, 431)	39 (-556, 633)	-240 (-834, 359)
	Quartile 2	**Quartile 3**	**Quartile 4**
Walk Score®	*mean=61, SD=5*	*mean=76, SD=4*	*mean=89, SD=6*
Model 1	-723 (-1954, 505)	-642 (-1826, 565)	-127 (-1257, 1044)
Model 2	255 (-393, 895)	-241 (-854, 381)	7 (-577, 600)
Model 3	114 (-524, 769)	-232 (-834, 360)	-204 (-782, 381)

[a] Quartile 1 served as the reference. (Quartile 1 means (standard deviations, SD): participant-reported walkability = -2.0 (SD 0.9); GIS-derived walkability = -3.0 (SD 0.6); audit-assessed walkability = -2.1 (SD 0.6); Walk Score® = 42 (SD 10))

[b] **Model 1:** Unadjusted; **Model 2:** Adjusted for age, sex, BMI, depressed mood, dog ownership, insulin use, immigrant status, and season; **Model 3 (participant-reported walkability):** Adjusted for age, sex, BMI, depressed mood, dog ownership, insulin use, immigrant status, season, and GIS-derived walkability; **Model 3 (GIS-derived walkability, audit-assessed walkability, and Walk Score®):** Adjusted for age, sex, BMI, depressed mood, dog ownership, insulin use, immigrant status, season, and participant-reported walkability.

GIS-derived walkability

Those living in the most compared to the least walkable neighbourhoods (Q4 versus Q1) completed 606 more steps per day (95% CrI: 8, 1203). The difference in steps between the second and first quartiles was similar in magnitude (783 more steps/day for the second quartile, 95% CrI: 168, 1406). Quartile 3 demonstrated no important differences with Quartile 1.

Audit-assessed walkability

No statistically significant association was observed for audit-assessed walkability and daily steps. The point estimates suggested a negative association (e.g., Model 3 Quartile 4 versus 1: -240 steps/day, 95% CI -834, 359), but the confidence intervals included zero (Table 3).

Walk Score®

Similar to audit-assessed walkability, no statistically significant association was observed for the Walk Score® (e.g., Model 3: Quartile 4 versus 1: -204 steps/day, 95% CI -782, 381; Table 3).

Other correlates of daily steps

While several potentially important predictors of daily steps emerged in univariate models (S3 Table, Appendix G), the factors that remained important in the fully adjusted model (i.e., adjusted for age, sex, BMI, depressed mood, dog ownership, insulin use, immigrant status, season, GIS-derived neighbourhood walkability, and participant-reported neighbourhood walkability; S4 Table, Appendix G) included age, BMI, absence of depressed mood, dog ownership, and summer/spring season. Every one-year decrement in age was associated with 106 more steps/day (95% CrI: 85, 127), every one-unit decrement in BMI was associated with 119 more steps/day (95% CrI: 82, 155), and absence of depressed mood was associated with 553 more steps/day (95% CrI: 90, 1023). Dog owners completed 646 more steps/day (95% CrI: 28, 1250). Participants completed 692 steps/day in the summer/spring compared to the fall/winter (95% CrI: 283, 1106).

Discussion

We examined the associations between multiple measures of walkability with daily steps in a sample of adults with type 2 diabetes. Our findings demonstrate that those individuals who gave a more favorable assessment of their neighbourhood's walkability took 1345 more steps per day than those individuals who had a less favorable assessment (Quartile 4 versus 1; 95% CI 718, 1976). This is equivalent to approximately 13.5% of the recommended steps per day. Although we found a positive association between neighbourhood walkability and daily steps for the second and fourth quartiles of GIS-derived neighbourhood walkability, more studies are needed to determine if these associations are clinically important. No important associations were observed for audit-assessed walkability or the Walk Score®. We identified several other important predictors of higher levels of walking among adults with type 2 diabetes. These included a demonstrable effect of absence of depressed mood, dog ownership and spring/summer (compared to fall/winter) season.

Our findings on the relationship between participant-reported walkability and daily steps are consistent with the recently published results from the 11-country International Physical Activity and the Environment Network (IPEN) Adult Study. In this study individuals who reported easier access to destinations and services were 17% more likely to achieve ≥420 minutes/week of MVPA, those who reported better neighbourhood aesthetics were 13% more likely to achieve ≥420 minutes/week of MVPA, and those who reported greater safety from crime were 14% more likely to achieve ≥420 minutes/week of MVPA [46].

We demonstrated that there is a beneficial association between GIS-derived neighbourhood walkability and daily steps in adults with type 2 diabetes. It remains unclear, however, if these benefits are clinically important. We did not find any important associations with daily steps for audit-based walkability or the Walk Score®. A possible explanation for a positive association for GIS-derived neighbourhood walkability but not for these two measures is that audit-based walkability and the Walk Score® capture different characteristics of home neighbourhoods. The audit-based walkability index captured finer-scale features of a neighbourhood environment (e.g., crossing aids and sidewalk conditions), and the Walk Score® captured the proximity of homes to 13 walkable destinations. This is in contrast to the GIS-derived measure of walkability, which captured three large-scale characteristics of urban designs (i.e., street connectivity, residential density and land use mix). It is possible that, in this population, larger-scale rather than finer-scale features of neighbourhoods may play slightly more of an important role in the total amount of walking that adults with type 2 diabetes achieve.

Our finding of a clear positive association for perceived neighbourhood walkability and a less clear association for more objective measures of neighbourhood walkability (i.e., GIS-derived, audit-based, and the Walk Score®) is in line with the pervious work. It has been estimated that there is a 30% mismatch between perceived and objectively assessed walkability [47, 48] and that the correlation between these measures is low [22, 47]. This suggests that these measures are capturing different aspects of walkability and thus, it is not unexpected that they would have different relationships with the same outcome of interest. Indeed, there is evidence of this elsewhere in the literature. For example, in a recent study of 5124 adults who were free of type 2 diabetes at baseline and who participated in the Multi-Ethnic Study of Atherosclerosis, participant-reported neighbourhood walkability (based on resources that support physical activity) was more strongly associated with lower risk of incident type 2 diabetes over 8.9 years of follow-up than GIS-derived neighbourhood walkability (i.e., HR=0.79, 95% CI 0.71, 0.88 *versus* HR=0.96, 95% CI 0.92, 0.99) [49].

In addition to better perceived (i.e., participant-reported) neighbourhood walkability, absence of depressed mood, dog ownership, and spring/summer (versus fall/winter) season were identified as important predictors of higher daily steps in adults with type 2 diabetes. Approximately one fourth of women and one sixth of men with diabetes have depressive symptoms [50, 51]. In a study of 2,646 primary care patients with type 2 diabetes, depressed patients were nearly two times more likely to be inactive than non-depressed patients (Odds Ratio (OR)=1.74, 95% CI: 1.32, 2.31) [52]. There is also evidence that higher levels of physical activity may lead to lower risk of incident depression. In a study of 1,947 older community-dwelling adults, higher physical activity was associated with a 17% decreased likelihood of developing depression over five years (OR=0.83, 95% CI: 0.73, 0.96) [53]. Our study is the first to quantify the association between depressed mood and biosensor-assessed daily steps in patients type 2 diabetes. We found that absence of depressed mood was associated with taking 553 more steps/day (95% CrI 90, 1023). Although we cannot draw conclusions regarding causality or directionality of the relationship, treating depressive symptoms might lead to increases in walking and/or facilitating increases in walking (e.g., by prescribing daily steps [54]) might alleviate symptoms of depression in adults with type 2 diabetes. In line with previous findings [55], we also determined that dog owners achieved 646 steps/day (95% CrI: 28, 1250) more than non-dog owners. Based on this, and evidence that encouraging dog walking among dog owners may increase their daily steps [56, 57], promoting dog walking may be an important point to leverage especially in populations where dog ownership may be high. The seasonal differences in daily steps that we identified were similar to those described in other studies [58-60]. In a previous analysis of this cohort, we demonstrated a -758 mean fall/winter to spring/summer difference in daily steps (95% CI -1037, -479) [32]. In this study, we confirmed that the association held independently of several covariates, including walkability. Given fall/winter declines in walking, public health and clinical strategies need to encourage and support maintenance of physical activity levels in fall and winter months.

We demonstrated that a high percentage of participants who completed the mailed questionnaire had regular access to a vehicle a car (79.1%) and that there is a negative graded association between neighbourhood walkability and regular vehicle access. We also demonstrated that respondents who had regular vehicle access accumulated 1426 fewer steps/day (95% CI -2752, -118) than respondents who did not have regular vehicle access (based on univariate linear regression analyses, S3 Table). Given a clear association between regular vehicle access and lower daily steps, discouraging reliance on cars may be a way to facilitate increases in physical activity. Even though including vehicle access in our models did not appear to alter our conclusions, it should be noted that we did not have enough data on vehicle access in order to fully investigate the role of this variable. To understand the role of vehicle access on the walkability-physical activity relationship in adults with type 2 diabetes, other studies will need to be conducted. Of particular interest are the mediating and moderating roles of vehicle access. There have been some studies conducted on the moderating and/or mediating roles of vehicle access in general adult and older adult populations [61, 62]. In a study of 2178 Swedish adults, vehicle access mediated 25% of the association between residential density and accelerometer-assessed MVPA and 34% of the association between land use mix and accelerometer-assessed MVPA [62]. Although vehicle access does not appear be an important moderator of the neighbourhood walkability-physical activity relationship in some studies [61, 62], it does in others [63, 64]. Differences are likely due to study populations and/or differences in exposure and outcome measurement [62].

Strengths of this study included objective assessments of exposures and outcome, assessment of residential self-selection multiple measures of walkability, and repeated measurements of daily steps over time. Repeated outcome measures increase the power to detect effects [65, 66]. An added strength was that our study is the first to examine the link between GIS-derived walkability and daily steps in North America adults with type 2 diabetes. Daily steps are of particular interest as they are more easily understood by patients and practitioners than activity counts or time spent in MVPA. It is important to note, however, that had we used another outcome (e.g., MVPA), it is possible that important associations may have emerged. We acknowledge some potential limitations. First, we cannot be definitive about the directionality or causality of the relationships. Because follow-up did not commence with the 'onset' of moving to a walkable neighbourhood, we cannot conclude that walkability led to higher steps. It remains possible that more active people perceive their neighbourhoods as more walkable and/or move to neighbourhoods that are. Second, we cannot make definitive conclusions regarding the neighbourhood walkability-walking relationship independent of vehicle access and residential self-selection. We collected these data in follow-up to an already completed study and thus were only able to obtain this information on a subsample of our study population. Our analyses regarding the role of these variables were exploratory. Third, our overall sample size limited the accuracy of the estimated effects. More definitive conclusions could be drawn had more data been available. Fourth, walkability cannot influence steps if one is not exposed to the environment. Although studies on location-based physical activity are emerging [67-69], more studies using Geographical Positioning Systems monitoring are needed to make a definitive connection between environmental exposure and behaviour [61]. Lastly, because differences in socio-demographic characteristics were observed between participants included and excluded from the final analyses (e.g., annual household income, ethnicity), the possibility of selection bias cannot be excluded.

Conclusions

Despite these potential limitations, there are some important conclusions that can be drawn from these analyses. Participant-reported walkability appears to be an important predictor of daily steps in adults with type 2 diabetes. There is a positive association between neighbourhood walkability and daily steps for the second and fourth quartiles of GIS-derived neighbourhood walkability, but more studies are needed to determine if these associations are clinically important. No important associations were observed for audit-assessed walkability or the Walk Score®. Residents' knowledge of neighbourhood features is a meaningful component of the concept of walkability and publicizing features that enhance walkability may lead to improvements in perceptions and ultimately higher daily steps. Season was confirmed to be an important predictor of daily steps as were several individual-level factors, including absence of depressed mood and dog ownership. Developing strategies that address individual-level and environmental factors in combination may prove useful for facilitating increases in total walking.

Acknowledgments

The authors thank Patrick Bélisle and Deborah Chan for their assistance with programming and data management, Max Halparin, Alexandre Poisson, and Elizabeth McNamee for conducting the neighbourhood audits, and Max Halparin for conducting the GIS mapping. This work was supported by an operating grant from the Canadian Institutes of Health Research (CIHR) (KD: MOP-79275), a Catalyst Grant (NAR and KD: 94431) from CIHR, and a grant from the Heart and Stroke Foundation of Canada (KD: G-12-000251). SHajna was supported by a Canadian Institutes of Health Research (CIHR) Doctoral Research Award. KD is supported through a Senior Clinician Scientist Award from the Fonds de Recherché Santé Québec. NAR was supported by a Fonds de Recherché Santé Québec (FRSQ) Career Award (Chercheurs Boursier Health and

Society) and the Canada Research Chair program (http://www.chairs-chaires.gc.ca). SHarper was supported by a Fonds de Recherché Santé Québec (FRSQ) Career Award (Chercheurs Boursier Junior 2).

SHajna conducted the statistical analyses and wrote the manuscript. KD designed and obtained the funding for the study, supervised the analyses and co-wrote the manuscript. NAR contributed to discussions regarding the study design, directed the in-field audit measurements, and co-wrote the manuscript. LJ provided guidance regarding the statistical analyses and reviewed the manuscript for content. SHarper reviewed the manuscript for content. All authors read and approved the final manuscript. The authors have no conflicts of interest to disclose.

References

1. Hajna S, Ross NA, Brazeau AS, Belisle P, Joseph L, Dasgupta K. Associations between neighbourhood walkability and daily steps in adults: a systematic review and meta-analysis. BMC Public Health. 2015;15(1):768. doi: 10.1186/s12889-015-2082-x. PubMed PMID: 26260474; PubMed Central PMCID: PMCPMC4532296.

2. Hajna S, Ross NA, Joseph L, Harper S, Dasgupta K. Neighbourhood walkability, daily steps and utilitarian walking in Canadian adults. BMJ Open. 2015;5(11):e008964. doi: 10.1136/bmjopen-2015-008964. PubMed PMID: 26603246.

3. De Greef K, Van Dyck D, Deforche B, De Bourdeaudhuij I. Physical environmental correlates of self-reported and objectively assessed physical activity in Belgian type 2 diabetes patients. Health Soc Care Community. 2011;19(2):178-88. doi: 10.1111/j.1365-2524.2010.00958.x. PubMed PMID: 20880106.

4. Taylor LM, Leslie E, Plotnikoff RC, Owen N, Spence JC. Associations of perceived community environmental attributes with walking in a population-based sample of adults with type 2 diabetes. Ann Behav Med. 2008;35(2):170-8. doi: 10.1007/s12160-008-9021-3. PubMed PMID: 18347894.

5. Thomas N, Alder E, Leese GP. Barriers to physical activity in patients with diabetes. Postgrad Med J. 2004;80(943):287-91. PubMed PMID: 15138320; PubMed Central PMCID: PMCPMC1742997.

6. Kannel WB, McGee DL. Diabetes and cardiovascular disease. The Framingham study. Jama. 1979;241(19):2035-8. Epub 1979/05/11. PubMed PMID: 430798.

7. Schondorf T, Lubben G, Karagiannis E, Erdmann E, Forst T, Pfutzner A. Increased prevalence of cardiovascular disease and risk biomarkers in patients with

unknown type 2 diabetes visiting cardiology specialists: results from the DIASPORA study. Diabetes & vascular disease research : official journal of the International Society of Diabetes and Vascular Disease. 2010;7(2):145-50. Epub 2010/04/13. doi: 10.1177/1479164109358241. PubMed PMID: 20382778.

8. Public Health Agency of Canada. What can happen if I have uncontrolled high blood pressure and what can I do to lower it 2009. Available from: http://www.phac-aspc.gc.ca.

9. Tudor-Locke CE, Bell RC, Myers AM, Harris SB, Lauzon N, Rodger NW. Pedometer-determined ambulatory activity in individuals with type 2 diabetes. Diabetes research and clinical practice. 2002;55(3):191-9. Epub 2002/02/19. PubMed PMID: 11850095.

10. Van Vrancken C, Bopp CM, Reis JP, DuBose KD, Kirtland KA, Ainsworth BE. The prevalence of leisure-time physical activity among diabetics in South Carolina. South Med J. 2004;97(2):141-4. Epub 2004/02/26. PubMed PMID: 14982262.

11. Korkiakangas EE, Alahuhta MA, Laitinen JH. Barriers to regular exercise among adults at high risk or diagnosed with type 2 diabetes: a systematic review. Health Promot Int. 2009;24(4):416-27. Epub 2009/10/02. doi: 10.1093/heapro/dap031. PubMed PMID: 19793763.

12. Casey D, De Civita M, Dasgupta K. Understanding physical activity facilitators and barriers during and following a supervised exercise programme in Type 2 diabetes: a qualitative study. Diabet Med. 2010;27(1):79-84. Epub 2010/02/04. doi: 10.1111/j.1464-5491.2009.02873.x. PubMed PMID: 20121893.

13. Huebschmann AG, Crane LA, Belansky ES, Scarbro S, Marshall JA, Regensteiner JG. Fear of injury with physical activity is greater in adults with diabetes than in adults without diabetes. Diabetes Care. 2011;34(8):1717-22. Epub 2011/06/28. doi: 10.2337/dc10-1801. PubMed PMID: 21700920; PubMed Central PMCID: PMC3142033.

14. Deshpande AD, Baker EA, Lovegreen SL, Brownson RC. Environmental correlates of physical activity among individuals with diabetes in the rural midwest. Diabetes Care. 2005;28(5):1012-8. PubMed PMID: 15855559.

15. Brownson RC, Hoehner CM, Day K, Forsyth A, Sallis JF. Measuring the built environment for physical activity: state of the science. Am J Prev Med. 2009;36(4 Suppl):S99-123 e12. doi: 10.1016/j.amepre.2009.01.005. PubMed PMID: 19285216; PubMed Central PMCID: PMCPMC2844244.

16. Saelens BE, Sallis JF, Frank LD. Environmental correlates of walking and cycling: findings from the transportation, urban design, and planning literatures. Ann Behav Med. 2003;25(2):80-91. Epub 2003/04/22. PubMed PMID: 12704009.

17. Frank LD, Saelens BE, Powell KE, Chapman JE. Stepping towards causation: do built environments or neighborhood and travel preferences explain physical activity, driving, and obesity? Soc Sci Med. 2007;65(9):1898-914. doi: 10.1016/j.socscimed.2007.05.053. PubMed PMID: 17644231.

18. Frumkin H, Frank L, Jackson R. Urban sprawl and public health: Designing, planning, and building for healthy communities. Washington, DC: Island Press; 2004.

19. Frank LD, Schmid TL, Sallis JF, Chapman J, Saelens BE. Linking objectively measured physical activity with objectively measured urban form: findings from

SMARTRAQ. Am J Prev Med. 2005;28(2 Suppl 2):117-25. doi: 10.1016/j.amepre.2004.11.001. PubMed PMID: 15694519.

20. Leslie E, Coffee N, Frank L, Owen N, Bauman A, Hugo G. Walkability of local communities: using geographic information systems to objectively assess relevant environmental attributes. Health Place. 2007;13(1):111-22. Epub 2006/01/03. doi: 10.1016/j.healthplace.2005.11.001. PubMed PMID: 16387522.

21. Saelens BE, Sallis JF, Black JB, Chen D. Neighborhood-based differences in physical activity: an environment scale evaluation. Am J Public Health. 2003;93(9):1552-8. Epub 2003/09/02. PubMed PMID: 12948979; PubMed Central PMCID: PMC1448009.

22. Hajna S, Dasgupta K, Halparin M, Ross NA. Neighborhood walkability: Field validation of geographic information system measures. Am J Prev Med. 2013;44(6):e51-5. doi: 10.1016/j.amepre.2013.01.033. PubMed PMID: 23683990.

23. Tudor-Locke C, Williams JE, Reis JP, Pluto D. Utility of pedometers for assessing physical activity: convergent validity. Sports Med. 2002;32(12):795-808. PubMed PMID: 12238942.

24. Tudor-Locke C, Williams JE, Reis JP, Pluto D. Utility of pedometers for assessing physical activity: construct validity. Sports Med. 2004;34(5):281-91. PubMed PMID: 15107007.

25. Schneider PL, Crouter S, Bassett DR. Pedometer measures of free-living physical activity: comparison of 13 models. Med Sci Sports Exerc. 2004;36(2):331-5. doi: 10.1249/01.MSS.0000113486.60548.E9. PubMed PMID: 14767259.

26. Yates T, Haffner SM, Schulte PJ, Thomas L, Huffman KM, Bales CW, et al. Association between change in daily ambulatory activity and cardiovascular events in

people with impaired glucose tolerance (NAVIGATOR trial): a cohort analysis. Lancet. 2013. Epub 2013/12/24. doi: 10.1016/S0140-6736(13)62061-9. PubMed PMID: 24361242.

27. Gilmour H. Physically active Canadians. Health Rep. 2007;18(3):45-65. Epub 2007/09/26. PubMed PMID: 17892251.

28. Tudor-Locke C, Bittman M, Merom D, Bauman A. Patterns of walking for transport and exercise: a novel application of time use data. Int J Behav Nutr Phys Act. 2005;2:5. Epub 2005/05/21. doi: 10.1186/1479-5868-2-5. PubMed PMID: 15904531; PubMed Central PMCID: PMC1181824.

29. Ford ES, Herman WH. Leisure-time physical activity patterns in the U.S. diabetic population. Findings from the 1990 National Health Interview Survey--Health Promotion and Disease Prevention Supplement. Diabetes Care. 1995;18(1):27-33. PubMed PMID: 7698044.

30. Mier N, Medina AA, Ory MG. Mexican Americans with type 2 diabetes: perspectives on definitions, motivators, and programs of physical activity. Prev Chronic Dis. 2007;4(2):A24. Epub 2007/03/17. PubMed PMID: 17362615; PubMed Central PMCID: PMC1893123.

31. Dasgupta K, Chan C, Da Costa D, Pilote L, De Civita M, Ross N, et al. Walking behaviour and glycemic control in type 2 diabetes: seasonal and gender differences--study design and methods. Cardiovasc Diabetol. 2007;6:1. doi: 10.1186/1475-2840-6-1. PubMed PMID: 17224062; PubMed Central PMCID: PMCPMC1783642.

32. Dasgupta K, Joseph L, Pilote L, Strachan I, Sigal RJ, Chan C. Daily steps are low year-round and dip lower in fall/winter: findings from a longitudinal diabetes cohort.

Cardiovasc Diabetol. 2010;9:81. doi: 10.1186/1475-2840-9-81. PubMed PMID: 21118567; PubMed Central PMCID: PMC3004821.

33. Schneider PL, Crouter SE, Lukajic O, Bassett DR, Jr. Accuracy and reliability of 10 pedometers for measuring steps over a 400-m walk. Med Sci Sports Exerc. 2003;35(10):1779-84. Epub 2003/10/03. doi: 10.1249/01.MSS.0000089342.96098.C4. PubMed PMID: 14523320.

34. Brownson RC, Chang JJ, Eyler AA, Ainsworth BE, Kirtland KA, Saelens BE, et al. Measuring the environment for friendliness toward physical activity: a comparison of the reliability of 3 questionnaires. Am J Public Health. 2004;94(3):473-83. Epub 2004/03/05. PubMed PMID: 14998817; PubMed Central PMCID: PMC1448279.

35. Hajna S, Dasgupta K, Halparin M, Ross NA. Neighborhood walkability: field validation of geographic information system measures. Am J Prev Med. 2013;44(6):e51-5. Epub 2013/05/21. doi: 10.1016/j.amepre.2013.01.033. PubMed PMID: 23683990.

36. DMTI Spatial Inc. Quebec Land Use Files (2008). Markham, ON.

37. DMTI Spatial Inc. Street Segment Files (2008). Markham, ON.

38. Statistics Canada. 2006 Canadian Census Files. Ottawa, Canada.

39. Christian HE, Bull FC, Middleton NJ, Knuiman MW, Divitini ML, Hooper P, et al. How important is the land use mix measure in understanding walking behaviour? Results from the RESIDE study. Int J Behav Nutr Phys Act. 2011;8:55. doi: 10.1186/1479-5868-8-55. PubMed PMID: 21631958; PubMed Central PMCID: PMCPMC3142478.

40. Clifton KJ, Smith LA, Rodriguez D. The Development and Testing of an Audit for the Pedestrian Environment. Landscape and Urban Planning. 2007;80(1-2):95-110.

41. Carr LJ, Dunsiger SI, Marcus BH. Validation of Walk Score for estimating access to walkable amenities. Br J Sports Med. 2011;45(14):1144-8. Epub 2010/04/27. doi: 10.1136/bjsm.2009.069609. PubMed PMID: 20418525.

42. Carr LJ, Dunsiger SI, Marcus BH. Walk score as a global estimate of neighborhood walkability. Am J Prev Med. 2010;39(5):460-3. Epub 2010/10/23. doi: 10.1016/j.amepre.2010.07.007. PubMed PMID: 20965384.

43. Okun A, Stein RE, Bauman LJ, Silver EJ. Content validity of the Psychiatric Symptom Index, CES-depression Scale, and State-Trait Anxiety Inventory from the perspective of DSM-IV. Psychological reports. 1996;79(3 Pt 1):1059-69. Epub 1996/12/01. PubMed PMID: 8969117.

44. Hoffmann K, Kroke A, Klipstein-Grobusch K, Boeing H. Standardization of dietary intake measurements by nonlinear calibration using short-term reference data. American Journal of Epidemiology. 2002;156(9):862-70. Epub 2002/10/25. PubMed PMID: 12397005.

45. Frank LD, Sallis JF, Saelens BE, Leary L, Cain K, Conway TL, et al. The development of a walkability index: application to the Neighborhood Quality of Life Study. Br J Sports Med. 2010;44(13):924-33. Epub 2009/05/02. doi: 10.1136/bjsm.2009.058701. PubMed PMID: 19406732.

46. Cerin E, Cain KL, Conway TL, Van Dyck D, Hinckson E, Schipperijn J, et al. Neighborhood environments and objectively measured physical activity in 11 countries. Med Sci Sports Exerc. 2014;46(12):2253-64. doi: 10.1249/MSS.0000000000000367. PubMed PMID: 24781892; PubMed Central PMCID: PMCPMC4232984.

47. Koohsari MJ, Badland H, Sugiyama T, Mavoa S, Christian H, Giles-Corti B. Mismatch between perceived and objectively measured land use mix and street connectivity: associations with neighborhood walking. J Urban Health. 2015;92(2):242-52. doi: 10.1007/s11524-014-9928-x. PubMed PMID: 25539783; PubMed Central PMCID: PMCPMC4411311.

48. Gebel K, Bauman AE, Sugiyama T, Owen N. Mismatch between perceived and objectively assessed neighborhood walkability attributes: prospective relationships with walking and weight gain. Health Place. 2011;17(2):519-24. doi: 10.1016/j.healthplace.2010.12.008. PubMed PMID: 21233002.

49. Christine PJ, Auchincloss AH, Bertoni AG, Carnethon MR, Sanchez BN, Moore K, et al. Longitudinal Associations Between Neighborhood Physical and Social Environments and Incident Type 2 Diabetes Mellitus: The Multi-Ethnic Study of Atherosclerosis (MESA). JAMA Intern Med. 2015;175(8):1311-20. doi: 10.1001/jamainternmed.2015.2691. PubMed PMID: 26121402.

50. Anderson RJ, Freedland KE, Clouse RE, Lustman PJ. The prevalence of comorbid depression in adults with diabetes: a meta-analysis. Diabetes Care. 2001;24(6):1069-78. Epub 2001/05/26. PubMed PMID: 11375373.

51. Adriaanse MC, Dekker JM, Heine RJ, Snoek FJ, Beekman AJ, Stehouwer CD, et al. Symptoms of depression in people with impaired glucose metabolism or type 2 diabetes mellitus: The Hoorn Study. Diabetic Medicine 2008;25(7):843-9.

52. Koopmans B, Pouwer F, de Bie RA, van Rooij ES, Leusink GL, Pop VJ. Depressive symptoms are associated with physical inactivity in patients with type 2

diabetes. The DIAZOB Primary Care Diabetes study. Fam Pract. 2009;26(3):171-3. Epub 2009/03/27. doi: 10.1093/fampra/cmp016. PubMed PMID: 19321598.

53. Strawbridge WJ, Deleger S, Roberts RE, Kaplan GA. Physical activity reduces the risk of subsequent depression for older adults. Am J Epidemiol. 2002;156(4):328-34. Epub 2002/08/16. PubMed PMID: 12181102.

54. Dasgupta K, Rosenberg E, Daskalopoulou SS, collaborators S. Step Monitoring to improve ARTERial health (SMARTER) through step count prescription in type 2 diabetes and hypertension: trial design and methods. Cardiovasc Diabetol. 2014;13:7. doi: 10.1186/1475-2840-13-7. PubMed PMID: 24393423; PubMed Central PMCID: PMC3893520.

55. Inoue S, Ohya Y, Odagiri Y, Takamiya T, Suijo K, Kamada M, et al. Sociodemographic determinants of pedometer-determined physical activity among Japanese adults. Am J Prev Med. 2011;40(5):566-71. doi: 10.1016/j.amepre.2010.12.023. PubMed PMID: 21496757.

56. Rhodes RE, Murray H, Temple VA, Tuokko H, Higgins JW. Pilot study of a dog walking randomized intervention: effects of a focus on canine exercise. Prev Med. 2012;54(5):309-12. doi: 10.1016/j.ypmed.2012.02.014. PubMed PMID: 22405707.

57. Schneider KL, Murphy D, Ferrara C, Oleski J, Panza E, Savage C, et al. An online social network to increase walking in dog owners: a randomized trial. Med Sci Sports Exerc. 2015;47(3):631-9. doi: 10.1249/MSS.0000000000000441. PubMed PMID: 25003777; PubMed Central PMCID: PMCPMC4286532.

58. Tudor-Locke C, Bassett DR, Swartz AM, Strath SJ, Parr BB, Reis JP, et al. A preliminary study of one year of pedometer self-monitoring. Ann Behav Med.

2004;28(3):158-62. Epub 2004/12/04. doi: 10.1207/s15324796abm2803_3. PubMed PMID: 15576253.

59. Hamilton SL, Clemes SA, Griffiths PL. UK adults exhibit higher step counts in summer compared to winter months. Ann Hum Biol. 2008;35(2):154-69. Epub 2008/04/23. doi: 10.1080/03014460801908058. PubMed PMID: 18428010.

60. Aoyagi Y, Shephard RJ. Steps per day: the road to senior health? Sports Med. 2009;39(6):423-38. Epub 2009/05/21. doi: 10.2165/00007256-200939060-00001. PubMed PMID: 19453204.

61. Ding D, Sallis JF, Norman GJ, Frank LD, Saelens BE, Kerr J, et al. Neighborhood environment and physical activity among older adults: do the relationships differ by driving status? J Aging Phys Act. 2014;22(3):421-31. doi: 10.1123/japa.2012-0332. PubMed PMID: 24084049.

62. Eriksson U, Arvidsson D, Gebel K, Ohlsson H, Sundquist K. Walkability parameters, active transportation and objective physical activity: moderating and mediating effects of motor vehicle ownership in a cross-sectional study. Int J Behav Nutr Phys Act. 2012;9:123. doi: 10.1186/1479-5868-9-123. PubMed PMID: 23035633; PubMed Central PMCID: PMCPMC3502165.

63. Van Dyck D, Deforche B, Cardon G, De Bourdeaudhuij I. Neighbourhood walkability and its particular importance for adults with a preference for passive transport. Health Place. 2009;15(2):496-504. doi: 10.1016/j.healthplace.2008.08.010. PubMed PMID: 18974020.

64. Kamada M, Kitayuguchi J, Inoue S, Kamioka H, Mutoh Y, Shiwaku K. Environmental correlates of physical activity in driving and non-driving rural Japanese

women. Prev Med. 2009;49(6):490-6. doi: 10.1016/j.ypmed.2009.09.014. PubMed PMID: 19769998.

65. Guo Y, Pandis N. Sample-size calculation for repeated-measures and longitudinal studies. Am J Orthod Dentofacial Orthop. 2015;147(1):146-9. doi: 10.1016/j.ajodo.2014.10.009. PubMed PMID: 25533082.

66. Guo Y, Logan HL, Glueck DH, Muller KE. Selecting a sample size for studies with repeated measures. BMC Med Res Methodol. 2013;13:100. doi: 10.1186/1471-2288-13-100. PubMed PMID: 23902644; PubMed Central PMCID: PMCPMC3734029.

67. Rodriguez DA, Brown AL, Troped PJ. Portable global positioning units to complement accelerometry-based physical activity monitors. Med Sci Sports Exerc. 2005;37(11 Suppl):S572-81. Epub 2005/11/19. PubMed PMID: 16294120.

68. Oliver M, Badland H, Mavoa S, Duncan MJ, Duncan S. Combining GPS, GIS, and accelerometry: methodological issues in the assessment of location and intensity of travel behaviors. J Phys Act Health. 2010;7(1):102-8. Epub 2010/03/17. PubMed PMID: 20231761.

69. Troped PJ, Wilson JS, Matthews CE, Cromley EK, Melly SJ. The built environment and location-based physical activity. Am J Prev Med. 2010;38(4):429-38. Epub 2010/03/24. doi: 10.1016/j.amepre.2009.12.032. PubMed PMID: 20307812.

CHAPTER EIGHT | Manuscript 6

Neighbourhood walkability and neighbourhood-based physical activity: An observational study of adults with type 2 diabetes

Samantha Hajna,[1] Yan Kestens,[2] Stella S. Daskalopoulou,[3] Lawrence Joseph,[1,5] Benoit Thierry,[2] Mark Sherman,[6] Luc Trudeau,[4] Rémi Rabasa-Lhoret,[7] Leslie Meissner,[8] Simon L. Bacon,[9,10] Lise Gauvin,[11] Nancy A. Ross,[1,12] Kaberi Dasgupta,[1,5] Diabetes, GPS, and Walkablilty Study Group[13]

International Journal of Behavioral Nutrition and Physical Activity. Under Review.

[1]Department of Epidemiology, Biostatistics and Occupational Health, McGill University, 1020 Pine Avenue West, Montreal, QC, Canada

[2]Centre de Recherche du Centre Hospitalier de l'Université de Montréal (CHUM), Tour St-Antoine, S02-340, 850 St-Denis, Montreal, QC, Canada

[3]Department of Medicine, Division of Internal Medicine, McGill University Health Centre, Montreal General Hospital, 1650 Cedar Avenue, C2.101.4, Montreal, QC, Canada

[4]Division of Internal Medicine, Jewish General Hospital, 3755 Cote Sainte-Catherine, Montreal, QC, Canada

[5]Department of Medicine, Division of Clinical Epidemiology, McGill University Health Centre, 687 Pine Avenue West, Montreal, QC, Canada

[6]Department of Medicine, Division of Endocrinology, McGill University Health Centre, 1001 Boulevard Decarie, Montreal, QC, Canada

[7]Institut de Recherches Cliniques de Montréal (IRCM) 110 avenue des Pins, Montréal, QC, Canada

[8]Department of Medicine, Division of Endocrinology, St. Mary's Hospital, 3830 Lacombe Avenue, Montreal, QC, Canada

[9]Montreal Behavioural Medicine Centre, Hôpital du Sacré-Cœur de Montréal, 5400 Boul. Gouin Ouest, Montréal, QC, Canada

[10]Department of Exercise Science, Concordia University, 7141 Sherbrooke Street West, Montreal, QC, Canada

[11]Département de médecine sociale et préventive, École de Santé Publique, Université de Montréal, 7101 avenue du Parc Montréal, QC, Canada

[12]Department of Geography, McGill University, 805 Sherbrooke Street West, Montreal, QC, Canada

[13]Study collaborators are listed at the end of the article

PREAMBLE

In Chapters 6 and 7, I presented the results of my studies in which I estimated the associations between neighbourhood walkability and daily steps in the general Canadian adult population (*Manuscript 4*) and in adults living with type 2 diabetes (*Manuscript 5*). I did not find evidence of any important associations between neighbourhood walkability and biosensor-assessed daily steps in the general Canadian adult population. In my study of adults with type 2 diabetes, people living in the highest quartile of neighbourhood walkability achieved 606 more steps/day (95% CrI 8, 1203) compared to people living in the lowest quartile of neighbourhood walkability. These results, however, were inconclusive and not graded across quartiles.

A limitation of the majority of research that has been conducted to date has been a lack of spatial matching between neighbourhood walkability and physical activity. Detecting an association between neighbourhood walkability and walking, may require precise estimation of the physical activity that occurs specifically within residential neighbourhoods.[179] This issue has been noted by numerous authors, including Giles-Corti and colleagues,[176] Saelens and colleagues,[149] Handy and colleagues,[178] Rodriguez and colleagues[177] and Troped and colleagues.[179] Thanks to recent advances in real-time monitoring technology that makes isolation of neighbourhood-based physical activity possible,[208] this issue can now be addressed more thoroughly. The objective of my last study (*Manuscript 6*) was to determine if refinement of exposure assessment (i.e., isolating physical activity occurring only within residential neighbourhoods) would lead to detectable associations between neighbourhood walkability and physical activity in adults with type 2 diabetes.

I conducted this study using integrated GPS-accelerometer technology. GPS monitoring is a powerful tool that has far reaching applications. Recent technological advances have increased the capability of GPS devices to record spatial data over time. This, coupled with concurrent reductions in cost and size have made the use of portable GPS monitoring increasingly popular in commercial and research settings, including geology,[210,223,224] farming,[210,225] and exercise science.[210,226] Due to the increased popularity of using GPS monitors in research, numerous studies have been conducted to test their feasibility, reliability and validity in tracking physical activity patterns of people over time and space. Overall, these studies have consistently indicated that GPS units provide accurate assessments of movement in time and space and may be especially powerful tools when linked with concurrently assessed accelerometer data.[210,227-229] I have addressed the validity of accelerometers in assessing physical activity in adults in Chapter 1 (Please refer to page 20). In brief, accelerometers, like GPS units, are highly powerful tools that provide accurate physical activity in adults.[220,230,231]

The objective of my doctoral work was to quantify the association between neighbourhood walkability and biosensor-assessed total walking as captured by daily steps. In this study, I was not able to assess daily steps since the algorithm used to convert the activity counts to daily steps has not been validated. Instead, I used the validated metric VeDBA (i.e., Vector of the Dynamic Body Acceleration) to assess total physical activity. VeDBA correlates with the rate of oxygen consumption[232] – an estimate of total energy expenditure.[233] Given that daily steps are approximate total habitual walking,[113,125,126] total daily steps are expected to correlate well with total VeDBA – particularly in populations for whom walking is the preferred and most common form of physical activity (e.g., adults with type 2 diabetes[137,217]). Indeed, this was the case in my study. The Spearmen correlation coefficient (R) between 7-day pedometer assessed daily steps and 7-day accelerometer assessed total VeDBA occurring anywhere was 0.6 (95% CI 0.4, 0.7). To make VeDBA conceptually more interpretable, I capitalized on pedometer data that was available in this study population by creating a linear regression equation with which I was able to approximate the number of daily steps that would be associated with the observed change in VeDBA.

In addition to conducting all of the data analyses and writing the manuscript, I designed the study under the guidance of my supervisors, led the writing of the Heart and Stroke Foundation grant that funded my study, led the recruitment of collaborating physicians and participants, followed up with participants, and managed the raw data. This manuscript has been submitted to ***International Journal of Behavioral Nutrition and Physical Activity (IJBNPA)*****.** *Please note:* Formatting has been retained as per *IJBNPA* submission guidelines.

ABSTRACT

Background

There is some evidence that diabetes incidence is lower among adults living in more walkable neighbourhoods. The association between walkability and physical activity (PA), the presumed mediator of this relationship, has not been carefully examined in adults with type 2 diabetes. We investigated the associations of walkability with total PA occurring within home neighbourhoods and overall irrespective of location.

Methods

Participants (n=97; 59.5±10.5 years) were recruited through clinics in Montréal (QC, Canada) and wore a GPS-accelerometer device for 7 days. Total PA was expressed as the total Vector of the Dynamic Body Acceleration. PA location was determined using a Global Positioning System (GPS) device (SIRF IV chip). Walkability (street connectivity, land use mix, population density) was assessed using Geographical Information Systems software. The cross-sectional associations between walkability and location-based PA was estimated using robust linear regressions adjusted for age, body mass index, sex, university education, season, car access, residential self-selection, and wear-time.

Results

A one standard deviation (SD) increment in walkability was associated with 10.4% of a SD increment in neighbourhood-based PA (95% confidence interval (CI) 1.2, 19.7) – equivalent to 165 more steps/day (95% 19, 312). Car access emerged as an important predictor of neighbourhood-based PA (Not having car access: 38.6% of a SD increment in neighbourhood-based PA, 95% CI 17.9, 59.3). Neither walkability nor car access were conclusively associated with overall PA.

Conclusions

Although walkability is associated with higher within-neighbourhood PA, it is not associated with higher overall PA. Other factors will need to be leveraged to facilitate meaningful increases in overall PA among adults with diabetes.

KEYWORDS

Type 2 diabetes
Physical activity
Accelerometry
Global Positioning Systems
Physical activity locations
Neighbourhood walkability
Environmental epidemiology
Health geography

BACKGROUND

Adults with type 2 diabetes have low average levels of physical activity [1, 2]. Even modest increases may lead to important reductions in the risk for diabetes-related complications [3, 4]. It has been suggested that enhancing neighbourhood walkability may help facilitate increases in physical activity, particularly in older adults and/or in those living with chronic conditions [5-7].

Urban planners consider walkable neighbourhoods to be characterized by a variety of services and destinations easily accessed through well-connected street networks [8, 9]. These emerge when demand for services is high, as in more densely populated areas [10, 11]. Based on data from general adult populations, residents of such neighbourhoods do report higher levels of utilitarian walking (e.g., walking to work) [12, 13]. There is a less consistent relationship between neighbourhood walkability and physical activity assessed objectively (i.e., with biosensor devices such as pedometers and accelerometers). While positive relationships have been delineated in Japan and in some European countries [14], the findings from North American studies are less clear [15, 16]. The relationship between neighbourhood walkability and physical activity has not been well-studied in type 2 diabetes, despite evidence of lower diabetes incidence in more walkable neighbourhoods [17, 18].

In the present study, we used an integrated Global Positioning System (GPS)-accelerometer device to isolate total physical activity occurring within home neighbourhoods and to link this to neighbourhood walkability in a cohort of adults with type 2 diabetes. We hypothesized that a true relationship between neighbourhood walkability and physical activity would be more apparent if physical activity specifically within the neighbourhood was considered. Two previous studies have investigated the relationship between neighbourhood walkability and residential neighbourhood-based physical activity intensity in adults and demonstrated a positive relationship between these factors [19, 20]. We build on this work by examining total levels of physical activity occurring both within home neighbourhoods (excluding inside homes) and overall physical activity irrespective of location in adults with type 2 diabetes.

METHODS

Participants and recruitment procedures

The study cohort was recruited between November 2012 and February 2015 during the baseline evaluations of an ongoing randomized controlled trial (Step Monitoring to Improve ARTERial Health, SMARTER; NCT0147520) [21]. The objective of SMARTER is to determine if physician-delivered step prescriptions lead to improvements in vascular disease risk among adults with type 2 diabetes or hypertension. Participants were ≥18 years of age at recruitment, under the care of a collaborating physician, and had a body mass index (BMI) between 25 and 40 kg/m^2. Participants with co-morbid conditions that would impede accurate measurement of physical activity (e.g., visual impairments) or adherence to study procedures were excluded from the study. Those participants with a physician-diagnosis of type 2 diabetes and willing to wear a GPS-accelerometer device for 7 consecutive days as part of their baseline assessment were enrolled into this study. SMARTER baseline assessment also included wearing a Yamax SW-701 pedometer with concealed viewing window for 7 days. All participants provided written informed consent. Procedures were approved by McGill University's Institutional Review Board (A08-M70-12B) and all participating institutions.

Geographic Information System-derived neighbourhood walkability

Residential neighbourhoods were approximated using 500-meter polygonal street network buffers around home addresses using Geographic Information System (GIS) software (ArcMap 10.1; ESRI, Redlands, CA) and digital maps. *Street connectivity* within each buffer was computed as the number of ≥3-way intersections/km^2. *Land use mix* was calculated using the entropy formula $(-1)\ \Sigma_k(p_k \ln p_k)/\ln N$, where p represented the proportion of land area devoted to a specific land use (k) in each buffer and N represented the number of land uses that were being assessed (i.e., 4; residential, commercial, institutional/governmental and recreational land uses). Street and land use files were obtained from DMTI CanMap Streetfiles [22]. *Population density* equaled the number of people per km^2 of the census dissemination block where the home was located (2011 Canada Census Population Counts File). A walkability index was calculated by summing the z-scores of these three measures (street connectivity, land use mix, population density). A higher index indicated greater walkability.

Location-based Physical Activity

Physical activity and location were assessed with research-grade devices that integrate a GPS monitor (SIRF IV chip) and a tri-axial accelerometer (ADXL 345, Analog Devices) into one unit (96 x 80 x 31.80 mm, 125 g). Participants wore the GPS-accelerometer device on their hip for 7 days during waking hours, except when showering, bathing, or swimming and were instructed to connect their unit to a charger every night before going to bed. After the 7-day monitoring period, the device was mailed back to the research center in a postage-paid envelope. Physical activity was expressed as total Vector of the Dynamic Body Acceleration (VeDBA) accumulated over the total valid wear-period. Dynamic Body Acceleration correlates well with the rate of oxygen consumption [23, 24]. For the purposes of our study, VeDBA (i.e., the dynamic component of body acceleration (m/s^2) integrated over a one-minute epoch) was summed over each participant's valid wear time. In line with previously established methods [25, 26], we retained only individuals with 4 or more valid wear days (i.e., at least 10 hours of valid data per day). Periods with 1 hour or more of consecutive accelerometer counts equal to zero were defined as non-wear time.

The GPS-accelerometer devices collected time-stamped latitudes and longitudes at 5-second intervals and raw accelerometer data at 50Hz on 3 axes. The location and accelerometer data were time-matched at the minute level. Participants' homes were identified based on the density and distribution of GPS fixes using a 'hot spot' kernel-based detection algorithm [27]. Each hot-spot was verified to ensure that it matched the residential address that was provided by the participants. Participants with a mismatched home addresses were removed from the analyses. A spatial join was performed between the neighbourhood buffers and the GPS tracks of each participant to identify all GPS coordinates falling within the neighbourhood buffer but outside of the homes. Total VeDBA associated with these "inside neighbourhood" coordinates was computed.

Pedometer-assessed Daily Steps

Daily steps were assessed for 7 consecutive days at the baseline SMARTER evaluation (Yamax SW-701; viewing windows concealed). Participants were provided with two pedometers. Pedometer A was worn for 7 consecutive days. Pedometer B remained in the postage-paid envelope and accounted for extra steps accumulated during the mailing process. Average daily steps were calculated as number of steps accumulated on Pedometer A minus number of steps accumulated on Pedometer B divided by the number of days the pedometer was worn. We created a robust linear regression model with which we established the relation between number of daily steps and observed increments in VeDBA.

Covariates

Season (spring/summer *versus* fall/winter) was defined based on the evaluation start date. Body mass index (BMI, kg/m^2) was computed from weight and height measurements taken by a trained research assistant. The following were queried by questionnaire: age, sex, time since diabetes diagnosis, home address, married/common-law status, university education, employment, ethnicity, immigrant status, dog ownership, smoking status, insulin use, ownership and/or regular access to a motorized vehicle, depressed mood (Center for Epidemiologic Studies-Depression Scale score ≥16) [28], perceived neighbourhood walkability, and the importance of a neighbourhood's walkability when choosing to move there.

Statistical Analyses

Descriptive statistics were produced, overall and by quartile of walkability. Associations between GIS-derived walkability and physical activity were assessed using robust linear regressions (m estimation with bisquare weighting) before and after adjustment for the following variables: age, BMI, sex, education, season, car access, residential self-selection and valid wear-time accumulated within neighbourhoods. Higher overall wear-time may allow an individual a greater opportunity to accumulate physical activity. Variables were retained based on theoretical importance and/or if they were identified based on correlation analyses (i.e., R≥0.2) as potential confounders or predictors of neighbourhood-based physical activity. All variables were standardized so that the effect estimates of the linear regression models represented the percent change in 1-standard deviation (SD) of physical activity for a 1-SD increment in the GIS-derived walkability index. We approximated the number of pedometer-assessed daily steps associated with the observed increment in accelerometer-assessed VeDBA using robust linear regression model. To aid in the interpretation of our results, robust linear regressions were used to explore the relationship between BMI across quartiles of neighbourhood walkability. All statistical analyses were conducted using SAS 9.3 (SAS Institute Inc., Cary, NC, USA).

RESULTS

Characteristics of Study Population

Over 70% of SMARTER participants eligible at the time of recruitment for this study agreed to participate (156/220) of whom 71.2% had ≥ 4 valid wear days and 62.2% had complete data on all variables of interest (Figure 1). Most were married/common-law (69.1%), university-educated (53.6%), employed (61.9%), and lived in the greater Montreal area (68.0%). Just over half were men (56.7%). The average age was 59.5 years (SD 10.5) and mean BMI was 31.5 kg/m^2 (SD 4.5). On average, participants had diabetes diagnosis for 10.3 years (SD 7.6) and accumulated 4,980 steps/day (SD 2,798 steps/day). The rates of employment were similar among men (63.6%) and women (59.5%). VeDBA occurring anywhere was 615,687 (SD 240,065) and VeDBA occurring specifically within the residential neighbourhoods (excluding at home) was 26,113 (SD 39149).

Neighbourhoods had an average land use mix of 0.3 (SD 0.2), 27 three or more-way intersections/km^2 (SD 14), and 8,915 residents/km^2 (SD 8,351) (Table 1). Walkability was moderate (average GIS-derived walkability score=0, SD 2.15, Range: -3.5, 5.3). The least walkable neighbourhoods (Quartile 1 versus 4) had the highest proportions university education (70.8% versus 52.0%), dog owners (29.2% versus 12.0%), and participants with regular car access (91.7% versus 64.0%) (Table 1). Participants who were excluded from the final analyses (59/156) lived in less walkable neighbourhoods and included a larger proportion of women and a lower proportion of participants who were university educated, employed, immigrants, and/or had depressed mood (Additional File 1, Appendix H). Those participants who were also excluded due to insufficient valid wear-time (i.e., 45 of these 59) included a larger proportion of individuals who had regular access to a car compared to those who were not excluded (n=97) (i.e., 81.8% versus 74.2%) (Additional File 1, Appendix H).

Multivariate Analyses

Before and after adjustment for age, BMI and sex (Models 1 and 2), small but clinically important associations were observed between neighbourhood walkability and daily steps. After further adjustment, these associations remained positive but included possibly clinically unimportant effects. In the fully adjusted model (Model 5) a 1-SD increment in walkability was associated with 10.4% of a SD increment in neighbourhood-based physical activity (95% confidence interval (CI) 1.2 to 19.7%; Table 2). This would be similar to taking 165 more steps per day (95% CI 19 to 312) within home neighbourhoods. No conclusive associations were observed between neighbourhood walkability and overall physical activity (i.e., that occurred anywhere; 0.7%, 95% CI -13.7 to 15.2%; Additional File 2, Appendix H).

Not having access to a car emerged as the strongest predictor of higher neighbourhood-based physical activity after adjustment for factors identified *a priori* as potential confounders and covariates (Table 3). Those participants who did not have regular car access accumulated

38.5% of a SD more in neighbourhood-based physical activity (95% CI 17.9, 59.3) compared to people who did have regular car access. This is equivalent to an increment of approximately 613 steps per day (95% CI 284 to 942). No conclusive association was observed between car access and overall levels of physical activity (11.1% of a SD increment in neighbourhood-based physical activity for participants with regular car access compared to participants without regular car access, 95% CI -21.3 to 43.5).

After adjustment for age, sex and education, there was a signaled but inconclusive association between neighbourhood walkability and BMI: Participants who lived in the most compared to the least walkable neighbourhoods (Quartile 4 versus Quartile 1) had a 1.6 kg/m^2 decrement in BMI (95% CI -4.1 to 0.9). This signaled association remained after further adjustment for total physical activity occurring anywhere (i.e., -1.5 kg/m^2, 95% CI -3.9 to 1.0).

DISCUSSION

Our study population achieved an average of 4,980 steps/day, placing them in the "sedentary" category according to the cut-offs proposed by Tudor-Locke [29] and well below the recommended target of 10,000 steps per day [26]. This is consistent with the findings of previous studies of adults with type 2 diabetes [2, 7]. Improving neighbourhood walkability has been suggested as a means of facilitating increases in walking [5-7]. Our analyses demonstrate that higher neighbourhood walkability is associated with somewhat higher levels of neighbourhood-based physical activity in adults with type 2 diabetes after adjustment for age, BMI, sex, education, season, car access, and residential self-selection. There was no conclusive evidence, however, that individuals living in walkable neighbourhoods accumulated higher levels of overall physical activity (i.e., activity inside the neighbourhoods and elsewhere). Not having regular access to a car was the most important predictor of neighbourhood-based physical activity.

While there is a small association between higher walkability and neighbourhood-based walking it is important to note that there is no conclusive evidence that those who lived in more walkable neighbourhoods accumulated more overall physical activity. This is consistent with our previous analysis of 2,949 Canadian adults who participated in Cycle 1 of the Canadian Health Measures Survey [30], but in contrast to data from Europe and Asia. In a recent meta-analysis of European and Japanese studies which also employed objective measures of neighbourhood walkability and walking, we demonstrated that adults who live in high compared to low walkable neighbourhoods accumulate overall 766 more steps per day [14]. Socio-environmental contexts may modify the neighbourhood walkability-total physical activity relationship. The beneficial role of neighbourhood walkability on physical activity may be smaller in North America than in Europe/Asia, due to sociocultural differences in physical activity preferences and greater reliance on cars in North America [31].

While some previous studies have demonstrated that not having a car [32, 33], is associated with higher levels of total physical activity, we are the first to show that this factor is associated with greater levels of physical activity occurring specifically within residential neighbourhoods. We demonstrated that those patients who had regular access to a car achieved approximately 613 steps/day less in their neighbourhoods (95% CI 284 to 942) than patients who did not have regular access to a car. This effect is on par with seasonal deficits in daily steps counts that we observed in another cohort of adults with type 2 diabetes living in Montreal [2]. There we found a deficit of 758 steps per day in the fall/winter compared to the spring/summer (95% CI -1,037 to -479). Given that this population is highly inactive and on average accumulates 4,980 steps per day, an increase of 613 steps per day represents 12.3% of this population's total daily steps (95% CI 5.7 to 18.9). Since three-quarters of our cohort had regular access to a car, reducing reliance on cars may be an effective way of facilitating increases in neighbourhood-based physical activity among adults with type 2 diabetes. It is important to note, however, that car access was not conclusively associated with overall physical activity in this population.

Recent evidence suggests that diabetes incidence is lower in more walkable neighbourhoods [17, 18, 34]. In a study of 214,882 recent immigrants and 1,024,380 long-term residents living in Toronto (Canada) living in less walkable neighbourhoods (based on population density, residential density, street connectivity, and the availability of retail stores and services) was associated with a higher incidence of diabetes after adjustment for age and area-level poverty (Lowest versus highest walkability quintile; Immigrant men: relative risk [RR] 1.58, 95% CI 1.42 to 1.75, Immigrant women: RR 1.67, 95% CI 1.48 to 1.88, Long-term resident men: RR 1.32, 95% CI 1.26 to 1.38, Long-term resident women: RR 1.24, 95% CI 1.18 to 1.31) [17]. Similarly, in an analysis of 512,061 adults living in Sweden, adults who live in the lowest decile of neighbourhood walkability (based on street connectivity, land use mix, and residential density) were found to have a 33% lower odds of developing diabetes over 4 years of follow-up (Odds Ratio (OR): 1.33; 95% CI 1.13 to 1.55) after adjustment for neighbourhood deprivation [18]. Total physical activity is the presumed link between neighbourhood walkability and diabetes incidence [17, 18]. It is surprising then that we did not observed an association between neighbourhood walkability and total physical activity. There are several possible explanations for this. First, the positive association between neighbourhood walkability and diabetes incidence, may be due to unmeasured variables such as foodscapes. More walkable neighbourhoods may have a greater availability of healthy food outlets that may reduce the risk of cardiometabolic complications. This theory is supported by our signaled albeit inconclusive finding that participants living in a more walkable neighbourhood may have had lower BMIs than participants living in less walkable neighbourhoods, even after adjustment for total physical activity. Another explanation may be confounding by socio-economic status. In the Toronto-based study, residual confounding was a possibility since area-level poverty was used as a proxy for individual-level income. This is supported by the fact that the association in the Swedish study was attenuated after additional adjustment for individual-level income as well as age, sex, and education (Adjusted OR: 1.16; 95% CI 1.00 to 1.34) [17]. Lastly, it is possible that our exclusion of a large subset of participants due to insufficient wear-time (i.e., 28.8%) may have biased our results towards the null. Participants who did not accumulate sufficient wear-time had greater car access (i.e., were likely less active) and lived in less walkable neighbourhoods. Had we been able to include these participants in our analyses a stronger association may have emerged.

There are several strengths to our study. First, we avoided biases arising from participants forgetting to wear one of the devices by combining our sensors into one device. This is an improvement over the two previously conducted studies [18], in which participants wore two separate devices. Other strengths include the use of objective measures of walkability and physical activity, and consideration of individual-level covariates and confounders. Some limitations should also be noted. First, our results may not be generalizable to all individuals with type 2 diabetes since only a unique subset of adults with type 2 diabetes may have agreed to participant in this study. Second, 28.8% of participants did not accumulate enough valid GPS-accelerometer data to be included in the final analyses. Although the mechanism by which these data are missing is unknown, not including these participants in our analyses may have biased our association towards the null. Lastly, since our pedometer-assessed daily steps were not location specific, our daily step estimates represent only approximations of the corresponding changes in VeDBA.

CONCLUSIONS

Our study demonstrates that although neighbourhood walkability may not be associated with overall levels of physical activity (i.e., activity inside the neighbourhoods and elsewhere) in adults with type 2 diabetes, there may be a small positive association with neighbourhood-based physical activity. Not having regular access to a car was the most important predictor of higher levels of neighbourhood-based physical activity among adults with type 2 diabetes. It remains to be evaluated if combining more walkable neighbourhoods with walking promotion interventions that discourage reliance on cars facilitates increases in total walking among adults with type 2 diabetes.

FUNDING

Funding for this work was through operating grants from the Heart and Stroke Foundation of Quebec (HSF G-12-000251) and the Canadian Institutes of Health Research (CIHR MOP-79275). SH was supported through a CIHR Doctoral Research Award. KD is supported through a Senior Clinician Scientist Award from the Fonds de Recherché du Québec-Santé. NAR is supported through the Canada Research Chair program (http://www.chairs-chaires.gc.ca).

AUTHORS' CONTRIBUTIONS

SH conducted all aspects of the study including participant recruitment, data collection, data management and analyses, the writing of the final manuscript and takes full responsibility for the work as a whole. KD and NAR conceived the study, oversaw all aspects of the study design, provided guidance on the statistical analyses, and reviewed and edited multiple drafts of the manuscript. YK, SSD, SB and LG were involved in the early design phases of this study. LJ provided guidance on the statistical analyses. BT converted the raw GPS and accelerometer data unto a usable format and provided guidance in the interpretation of these data. MS, LT and RRL played a key role in the recruitment of participants into this study. All authors reviewed and approved the final manuscript.

ACKNOWLEDGEMENTS

The authors would like to thank Deborah Chan for her support in data collection, data management, and participant recruitment. The authors would also like to thank Anne-Sophie Brazeau and Corinne Suppère for their help in the recruitment and assessment of participants.

The Diabetes, GPS, and Walkablilty Study Group includes a subgroup of the SMARTER Trial (NCT0147520) collaborators who were invaluable in the recruitment of patients into this study. They include Dr. Sabiha Awan, Dr. Alexis Baass, Dr. Jean-Marie Boutin, Dr. Candace Lee, Dr. Carolina Capelle, Dr. Joanna Caron, Dr. Stavroula Christopolous, Dr. Karen Dahan, Dr. Maxine Dumas-Pilon, Dr. Roy Eappen, Dr. Leah Feldman, Dr. Natasha Garfield, Dr. Dominique Garrell, Dr. Lawrence Green, Dr. Walter Gregory, Dr. Wen Hu, Dr. Sofia Hussaini, Dr. John Hughes, Dr. Catherine Kudo, Dr. April Kinghorn, Dr. Evelyn Kyle, Dr. Leonora Lalla, Dr. Andrea Lalonde, Dr. Pierre Larochelle, Dr. Khue Ly, Dr. Richard Mackler, Dr. Agnieszka Majdan, Dr. Goldie Marmor, Dr. Sara Meltzer, Dr. Hortensia Mircescu, Dr. David Morris, Dr. Kimberly Munro, Dr. Vivian Petropoulos, Dr. Barry Posner, Dr. Brent Richards, Dr. Juan Rivera, Dr. Ghislaine Roederer, Dr. Samantha Sacks, Dr. Alicia Schiffrin, Dr. David Shannon, Dr. Raymond Sorge, Dr. Donald Sproule, Dr. Susan Still, Dr. Robert Wistaff, Dr. Mark Yaffe, Dr. Jean-Francois Yale and Dr. Hans Zingg.

REFERENCES

1. Tudor-Locke CE, Bell RC, Myers AM, Harris SB, Lauzon N, Rodger NW. Pedometer-determined ambulatory activity in individuals with type 2 diabetes. Diabetes Res Clin Pract. 2002;55:191-199.
2. Dasgupta K, Joseph L, Pilote L, Strachan I, Sigal RJ, Chan C. Daily steps are low year-round and dip lower in fall/winter: findings from a longitudinal diabetes cohort. Cardiovasc Diabetol. 2010;9:81.
3. Gregg EW, Gerzoff RB, Caspersen CJ, Williamson DF, Narayan KM. Relationship of walking to mortality among US adults with diabetes. Arch Intern Med. 2003;163:1440-1447.
4. Yates T, Haffner SM, Schulte PJ, Thomas L, Huffman KM, Bales CW, et al. Association between change in daily ambulatory activity and cardiovascular events in people with impaired glucose tolerance (NAVIGATOR trial): a cohort analysis. Lancet. 2014;383:1059-1066.
5. Hirsch JA, Winters M, Ashe MC, Clarke P, McKay H. Destinations That Older Adults Experience Within Their GPS Activity Spaces Relation to Objectively Measured Physical Activity. Environ Behav. 2016;48:55-77.
6. Chaudhury H, Campo M, Michael Y, Mahmood A. Neighbourhood environment and physical activity in older adults. Soc Sci Med. 2016;149:104-113.
7. De Greef K, Van Dyck D, Deforche B, De Bourdeaudhuij I. Physical environmental correlates of self-reported and objectively assessed physical activity in Belgian type 2 diabetes patients. Health Soc Care Community. 2011;19:178-188.

8. Saelens BE, Sallis JF, Frank L. Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures. Annals of Behavioural Medicine. 2003;25:80-91.

9. Leslie E, Coffee N, Frank L, Owen N, Bauman A, Hugo G. Walkability of local communities: using geographic information systems to objectively assess relevant environmental attributes. Health Place. 2007;13:111-122.

10. Frank LD, Schmid TL, Sallis JF, Chapman J, Saelens BE. Linking objectively measured physical activity with objectively measured urban form: findings from SMARTRAQ. Am J Prev Med. 2005;28:117-125.

11. Frank L. Land use and transportation interaction: Implications on public health and quality of life. Jouranl of Planning Education and Research. 2000;20:6-22.

12. McCormack GR, Shiell A. In search of causality: a systematic review of the relationship between the built environment and physical activity among adults. Int J Behav Nutr Phys Act. 2011;8:125.

13. Van Holle V, Deforche B, Van Cauwenberg J, Goubert L, Maes L, Van de Weghe N, et al. Relationship between the physical environment and different domains of physical activity in European adults: a systematic review. BMC Public Health. 2012;12:807.

14. Hajna S, Ross NA, Brazeau A, Bélisle P, Joseph L, Dasgupta K. Associations between neighbourhood walkability and daily steps in adults: A systematic review and meta-analysis. BMC Public Health. 2015;In Press.

15. Oakes JM, Forsyth A, Schmitz KH. The effects of neighborhood density and street connectivity on walking behavior: the Twin Cities walking study. Epidemiol Perspect Innov. 2007;4:16.

16. Tuckel P, Milczarski W. Walk Score(TM), Perceived Neighborhood Walkability, and walking in the US. Am J Health Behav. 2015;39:242-256.

17. Booth GL, Creatore MI, Moineddin R, Gozdyra P, Weyman JT, Matheson FI, et al. Unwalkable neighborhoods, poverty, and the risk of diabetes among recent immigrants to Canada compared with long-term residents. Diabetes Care. 2013;36:302-308.

18. Sundquist K, Eriksson U, Mezuk B, Ohlsson H. Neighborhood walkability, deprivation and incidence of type 2 diabetes: a population-based study on 512,061 Swedish adults. Health Place. 2015;31:24-30.

19. Rodriguez DA, Brown AL, Troped PJ. Portable global positioning units to complement accelerometry-based physical activity monitors. Med Sci Sports Exerc. 2005;37:S572-581.

20. Troped PJ, Wilson JS, Matthews CE, Cromley EK, Melly SJ. The built environment and location-based physical activity. Am J Prev Med. 2010;38:429-438.

21. Dasgupta K, Rosenberg E, Daskalopoulou SS, collaborators S. Step Monitoring to improve ARTERial health (SMARTER) through step count prescription in type 2 diabetes and hypertension: trial design and methods. Cardiovasc Diabetol. 2014;13:7.

22. DMTI Spatial Inc.: Quebec Land Use Files (2008). Markham, ON.

23. Qasem L, Cardew A, Wilson A, Griffiths I, Halsey LG, Shepard EL, et al. Tri-axial dynamic acceleration as a proxy for animal energy expenditure; should we be summing values or calculating the vector? PLoS One. 2012;7:e31187.

24. Halsey LG, Shepard EL, Hulston CJ, Venables MC, White CR, Jeukendrup AE, et al. Acceleration versus heart rate for estimating energy expenditure and speed during

locomotion in animals: tests with an easy model species, Homo sapiens. Zoology (Jena). 2008;111:231-241.

25. Hawkins MS, Storti KL, Richardson CR, King WC, Strath SJ, Holleman RG, et al. Objectively measured physical activity of USA adults by sex, age, and racial/ethnic groups: a cross-sectional study. Int J Behav Nutr Phys Act. 2009;6:31.

26. Colley RC, Garriguet D, Janssen I, Craig CL, Clarke J, Tremblay MS. Physical activity of Canadian adults: accelerometer results from the 2007 to 2009 Canadian Health Measures Survey. Health Rep. 2011;22:7-14.

27. Thierry B, Chaix B, Kestens Y. Detecting activity locations from raw GPS data: a novel kernel-based algorithm. Int J Health Geogr. 2013;12:14.

28. Radloff LS. The CES-D Scale: A Self-Report Depression Scale for Research in the General Population. Applied Psychological Measurement. 1977;1:385-401.

29. Tudor-Locke C, Hatano Y, Pangrazi RP, Kang M. Revisiting "how many steps are enough?" Med Sci Sports Exerc. 2008;40:S537-543.

30. Hajna S, Ross NA, Joseph L, Harper S, Dasgupta K. Neighbourhood walkability, daily steps and utilitarian walking in Canadian adults. BMJ Open. 2015;5:e008964.

31. The World Bank Group. Worldwide Passenger Cars (per 1,000 people). 2007.

32. Lachapelle U, Frank LD. Transit and health: mode of transport, employer-sponsored public transit pass programs, and physical activity. J Public Health Policy. 2009;30 Suppl 1:S73-94.

33. Shoham DA, Dugas LR, Bovet P, Forrester TE, Lambert EV, Plange-Rhule J, et al. Association of car ownership and physical activity across the spectrum of human

development: Modeling the Epidemiologic Transition Study (METS). BMC Public Health. 2015;15:173.

34. Glazier RH, Creatore MI, Weyman JT, Fazli G, Matheson FI, Gozdyra P, et al. Density, destinations or both? A comparison of measures of walkability in relation to transportation behaviors, obesity and diabetes in Toronto, Canada. PLoS One. 2014;9:e85295.

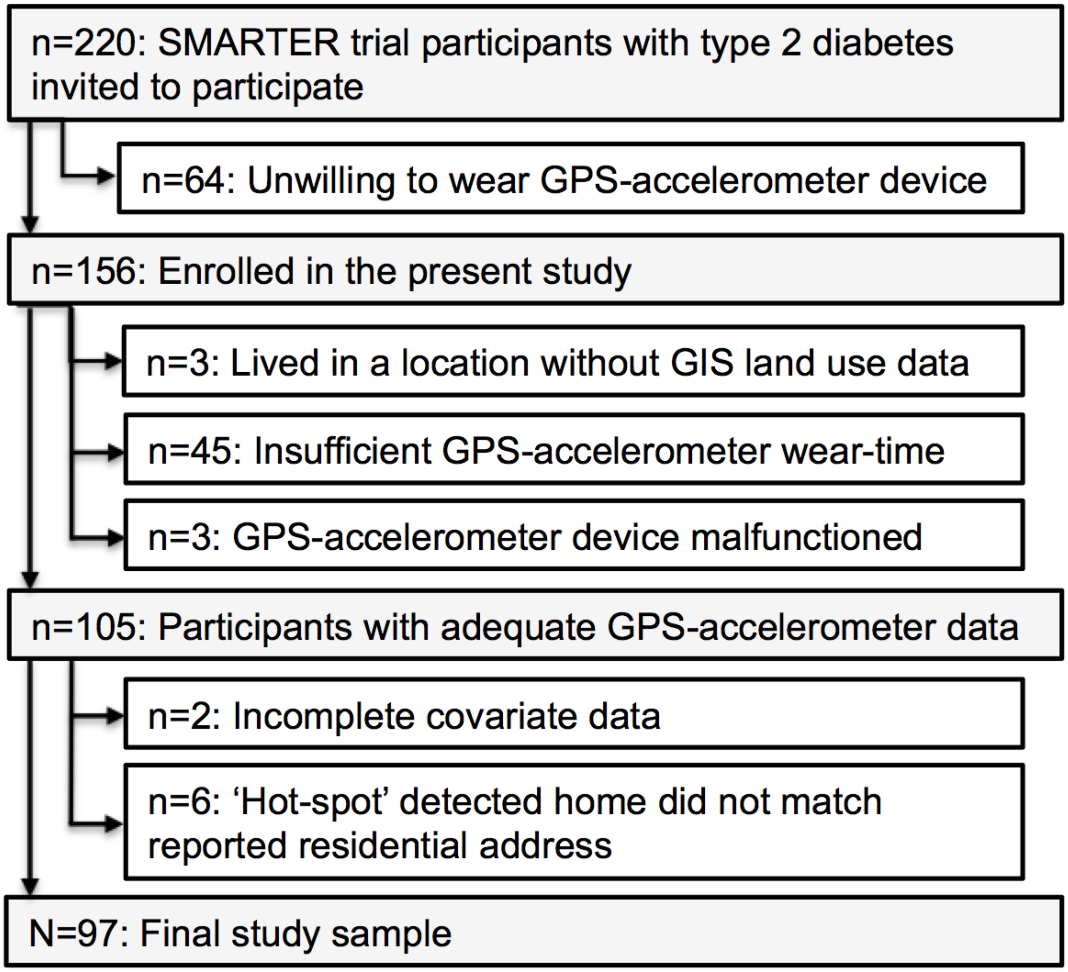


Figure 1 Selection of study cohort

Table 1 Characteristics of study population (n=97).

	Overall	**Quartile of Neighbourhood Walkability**[a]			
	mean (SD)	***Quartile 1*** mean (SD)	***Quartile 2*** mean (SD)	***Quartile 3*** mean (SD)	***Quartile 4*** mean (SD)
Age, *years*	59.5 (10.5)	60.6 (12.5)	58.8 (7.9)	57.7 (11.0)	60.6 (10.5)
Body mass index, kg/m^2	31.5 (4.5)	32.2 (4.9)	32.6 (4.9)	30.9 (4.0)	30.5 (3.9)
Time since diabetes diagnosis, *years*	10.3 (7.6)	9.9 (8.3)	9.6 (8.3)	10.8 (5.7)	11.1 (8.0)
Years at current residential address	18.9 (13.9)	22.9 (14.1)	15.9 (10.8)	20.1 (14.4)	17.0 (15.7)
Daily steps	4,980 (2,798)	4,261 (1,970)	5,957 (3,214)	4,256 (2,548)	5,359 (3,026)
Residential self-selection	0.001 (0.93)	-0.48 (0.71)	-0.12 (0.90)	0.06 (0.85)	0.53 (0.96)
Number of days with valid wear time	5.9 (1.0)	6.0 (1.0)	5.8 (1.1)	5.6 (0.9)	6.0 (1.1)
Total valid monitoring wear-time overall, *hours*	86.1 (21.1)	90.6 (21.0)	84.3 (21.8)	83.7 (20.3)	85.9 (21.7)
Total valid monitoring wear-time in neighbourhoods, *hours*	1.7 (2.8)	0.8 (0.5)	1.5 (1.3)	2.6 (5.3)	1.9 (1.5)
Proportion of time in neighbourhood, %	1.9 (2.4)	0.8 (0.6)	1.9 (2.1)	2.6 (3.7)	2.3 (2.0)
Total VeDBA					
Overall	615,687 (240,065)	601,822 (292,986)	619,913 (218,942)	611,492 (229,354)	628,632 (227,385)
In residential neighbourhoods (excluding home)	26,113 (39,149)	12,021 (13,781)	23,811 (27,747)	36,999 (67,888)	31,929 (24,518)
Street connectivity, *number of ≥3 way intersections/km*^{2}	27 (14)	14 (6)	26 (9)	30 (8)	37 (18)
Land use mix (Score range: 0 to 1)	0.30 (0.23)	0.04 (0.07)	0.21 (0.16)	0.44 (0.15)	0.50 (0.17)
Population density, *population count/km*^{2}	8,915 (8,351)	3,920 (2480)	4,422 (2,421)	8,462 (5,090)	18,621 (9,958)
	%	%	%	%	%
Women	43.3	33.3	32.0	60.9	48.0
Married/common-law	69.1	70.8	68.0	73.9	64.0
University education	53.6	70.8	60.0	30.4	52.0
Employed	61.9	58.3	64.0	65.2	60.0
Immigrant	51.6	45.8	44.0	56.5	60.0
Depressed mood	30.9	29.2	16.0	43.5	36.0
Dog ownership	16.5	29.2	12.0	13.0	12.0
Ever smoker	44.3	54.2	48.0	26.1	48.0
Insulin use	30.9	33.3	20.0	26.1	44.0
Car access	74.2	91.7	80.0	60.9	64.0
Spring/summer assessment (*versus* fall/winter)	40.2	33.3	24.0	47.8	56.0

[a] Quartile cut-offs for the GIS-derived walkability index: Quartile 1: < -1.91 (n=24); Quartile 2: ≥-1.91<-0.04 (n=25); Quartile 3: ≥-0.04<1.40 (n=23); Quartile 4: ≥1.40 (n=25); Neighbourhood walkability was based on polygonal-shaped buffers. [b] Proportion calculated as the minutes in each location divided by the total valid wear-minutes.

Table 2 Linear regression estimates for the associations between neighbourhood walkability and neighbourhood-based total VeDBA with corresponding changes in daily steps (n=97).

	Percent change in one SD of total VeDBA (95% confidence intervals)[a,b]	Corresponding change in daily steps (95% confidence intervals)[c]
Model 1	21.2 (12.8 to 29.6)	337 (203 to 470)
Model 2	17.6 (9.3 to 26.0)	280 (148 to 413)
Model 3	13.9 (5.2 to 22.6)	221 (83 to 359)
Model 4	10.0 (0.7 to 19.3)	159 (11 to 307)
Model 5	10.4 (1.2 to 19.7)	165 (19 to 312)

[a] **Model 1:** Unadjusted. **Model 2:** Adjusted for age, BMI, sex. **Model 3:** Adjusted for age, BMI, sex, university, and season. **Model 4:** Adjusted for age, BMI, sex, university, season, car access and residential self-selection. **Model 5:** Adjusted for age, BMI, sex, university, season, car access, residential self-selection and valid wear-time.

[b] Estimates represent the percent change in one standard deviation of total VeDBA (95% confidence interval) occurring within home neighbourhoods (excluding homes) for every one-standard deviation increase in the GIS-derived neighbourhood walkability index. Calculated by multiplying the original estimate by the standard deviation of the walkability index (i.e., 2.16), dividing the result by the SD of the outcome (i.e., 39,149.22) and multiplying by 100.

[c] Calculated using the following formula: daily steps=-548+0.0089*total VeDBA occurring anywhere)*(% change in one SD of VeDBA occurring in neighbourhood/100) where VeDBA occurring anywhere equals one SD of VeDBA occurring anywhere (i.e., 240,065.36)

Table 3 Linear regression estimates for the associations between socio-demographic, individual, and environmental factors and neighbourhood-based total VeDBA with corresponding changes in daily steps (n=97).[a]

	Percent change in one SD of total VeDBA (95% confidence intervals)[b]	Corresponding change in daily steps (95% confidence intervals)[c]
Age, *years*	-0.01 (-0.9 to 0.8)	-0.1 (-14 to 14)
Women	-8.5 (-26.5 to 9.4)	-135 (-421 to 150)
Body mass index, *kg/m*^{2}	-1.2 (-3.2 to 0.9)	-19 (-51 to 14)
University educated (yes *versus* no)	-8.8 (-26.8 to 9.1)	-140 (-425 to 144)
Spring/summer assessment (*versus* fall/winter)	16.1 (-1.2 to 33.4)	256 (-19 to 531)
Regular car access	-38.6 (-59.3 to -17.9)	-613 (-942 to -284)
Residential self-selection score	5.3 (-4.5 to 15.1)	84 (-72 to 240)
Valid wear-time, *minutes*	0.01 (-0.002 to 0.01)	0.1 (-0.03 to 0.2)

[a] This fully adjusted model is additionally adjusted for GIS-derived neighbourhood walkability.

[b] Effect estimates represent the percent change in one standard deviation of total VeDBA occurring in home neighbourhoods (excluding homes) for every one-unit increase in the predictor of interest. Calculated by dividing the original beta estimate by the standard deviation of VeDBA (occurring within home neighbourhoods but excluding homes) (i.e., 39,149.22) and multiplying by 100.

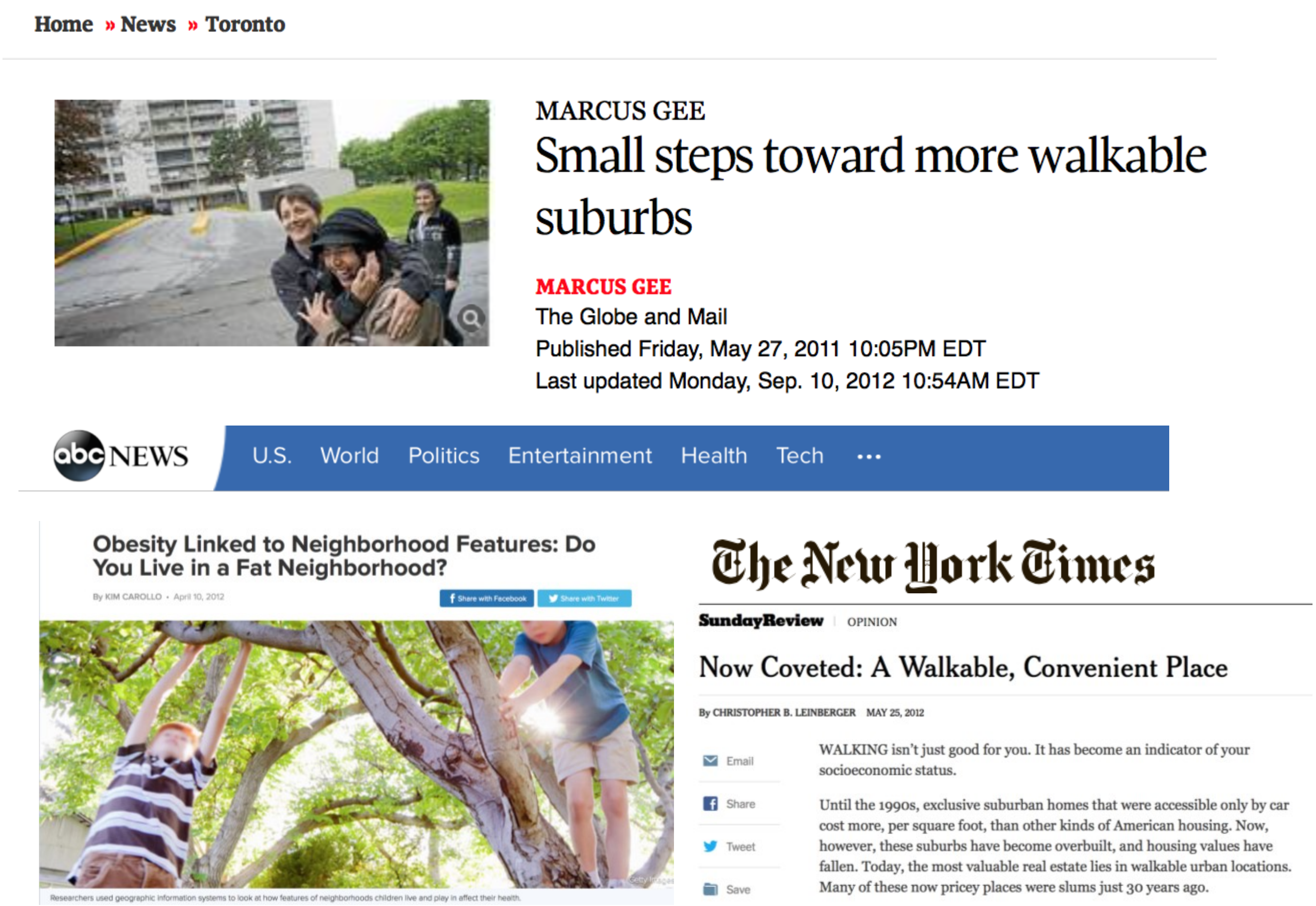
[c] Calculated using the following formula: daily steps=-548+0.0089*total VeDBA occurring anywhere)*(% change in one SD of VeDBA occurring in neighbourhood/100) where VeDBA occurring anywhere equals one SD of VeDBA occurring anywhere (i.e., 240,065.36)

CHAPTER NINE │Conclusion

Together, the results of my six manuscripts have allowed to me to answer my research question of interest: *Do people who live in more walkable neighbourhoods walk more than people who live in less walkable neighbourhoods?* In the first section of this chapter I provide a broad overview of my doctoral work and the key contributions that I have made in moving this field forward. In addition to helping me answer my research question, there were numerous other substantive contributions that each of my six manuscripts made to the neighbourhoods and physical activity literature. In the second section of this chapter I outline these specific contributions. I conclude with a summary of the strengths and limitations of my doctoral work, make suggestions for future major research directions, and provide several closing remarks.

What has my PhD work added to the field of neighbourhood walkability-physical activity research?

Since 2000 many studies have been conducted on the association between neighbourhood walkability and physical activity in adults. These studies have been published in leading academic journals (e.g., *Environmental Health Perspectives*,[186] the *American Journal of Preventative Medicine*,[62] and *Preventive Medicine*[196]) and the results have been highlight in popular media outlets, such as the Globe and Mail, ABC News, and the New York Times (Figure 9.1).



MARCUS GEE

Small steps toward more walkable suburbs

MARCUS GEE
The Globe and Mail
Published Friday, May 27, 2011 10:05PM EDT
Last updated Monday, Sep. 10, 2012 10:54AM EDT

Obesity Linked to Neighborhood Features: Do You Live in a Fat Neighborhood?

By KIM CAROLLO · April 10, 2012

Researchers used geographic information systems to look at how features of neighborhoods children live and play in affect their health.

Now Coveted: A Walkable, Convenient Place

By CHRISTOPHER B. LEINBERGER MAY 25, 2012

WALKING isn't just good for you. It has become an indicator of your socioeconomic status.

Until the 1990s, exclusive suburban homes that were accessible only by car cost more, per square foot, than other kinds of American housing. Now, however, these suburbs have become overbuilt, and housing values have fallen. Today, the most valuable real estate lies in walkable urban locations. Many of these now pricey places were slums just 30 years ago.

Figure 9.1 Media covering the link between neighbourhood walkability and health (Articles taken from www.theglobeandmail.com, abcnews.go.com, www.nytimes.com)

The research that has been conducted over the last 15 years has consistently linked higher neighbourhood walkability to higher self-reported utilitarian walking. The evidence base for total walking, the arguably more salient outcome for health, however, remained unclear. There are several likely explanations the mixed associations for total walking. First, there has been a heavy reliance on self-reported measures of neighbourhood walkability and/or total walking. Use of objective measures of exposures and outcomes is needed to better estimate this association. As noted in Chapter 2, studies in which researchers assess physical activity using biosensors (e.g., pedometers) have been shown to be 18% less likely to find important effects compared to studies in which researchers assess physical activity using participant reports.[203] Second, there has been a heavy reliance on statistical significance rather than on the quantification of the observed effects using interpretable effect estimates and corresponding variance estimates. As I described in Chapter 2, this has greatly limited our understanding of the degree to which leveraging neighbourhood designs may enable people to achieve higher levels of physical activity. This is because a statistically significant result (e.g., a p-value of <0.05) may have no clinical importance, leading to the false impression that neighbourhood walkability matters, when in fact it may not. Measurement and delineation of both magnitude and precision are important in health research. As a student of epidemiology, I was well positioned to quantify these in my work. The third limitation has been a lack of adequate control of confounding in many previously conducted studies. Either important potential confounders (e.g., car access, residential self-selection) have not been accounted for or crude proxies that are subject to residual confounding have been used instead (e.g., neighbourhood-level rather than individual-level income). In studies where researchers have carefully accounted for confounding (e.g., using matched sampling designs[84]), null associations between neighbourhood walkability and total walking/total physical activity have been reported. **The aim of my doctoral research was to elucidate the neighbourhood walkability-total walking/physical activity relationship in the Canadian context using 1) objective measures of exposures and outcomes 2) interpretable effect estimates with corresponding variance estimates and 3) accounting (as much as possible) for important potential confounders of the walkability-physical activity relationship.**

This brought me to the development of my six manuscripts. My aim in *Manuscript 1* was to synthesize our current state of knowledge on the association between GIS-derived neighbourhood walkability and biosensor assessed daily steps in adults. Based on data from Europe and Japan, I demonstrated that adults who live in high compared to low walkable neighbourhoods accumulate 766 more steps per day. In this Manuscript, I also identified a need for comparable studies to be conducted in North America – particularly in light of evidence from North America using self-reported measures of physical activity that neighbourhood walkability is not association with the total walking in adults.[61,62]

Now that I established a clear benefit of neighbourhood walkability on total walking in adults living in Europe and Japan (*Manuscript 1*) and that the measures that I would be using to capture neighbourhood walkability were valid (*Manuscripts 2* and *3*), the stage was set for me to investigate this association in a large sample of Canadian adults. In *Manuscript 4* I demonstrated that, when using objective measures of both the exposure and the outcome, no important association exists between neighbourhood walkability and total walking in Canada.

This led me to wonder whether an association could be detected in adults who may be particularly sensitive to the walkable features of their neighbourhoods. I investigated this association using an existing cohort of adults with type 2 diabetes on whom I had repeated measures of physical activity over time (*Manuscript 5*). In this study I found that adults living in the most compared to the least walkable neighbourhoods (Quartile 4 *versus* 1) achieved 606 more steps/day (95% CrI 8, 1203). While there was evidence of a small positive association between the most and least walkable neighbourhoods, the results were inconclusive and not graded across quartiles.

This led me to my final study (*Manuscript 6*). The major limitation of the studies that have been conducted to date, including my two substantive studies (*Manuscripts 4* and *5*), has been a lack of spatial matching between exposures and outcomes. Linking neighbourhood walkability to walking that does not necessarily occur in the neighbourhood may be diluting any associations that might exist. The objective of my sixth manuscript was to test this hypothesis in a clinical sample of adults living with type 2 diabetes. In this study I demonstrated that there is indeed a positive association between neighbourhood walkability and neighbourhood-based total physical activity (i.e., when there is a precise spatial match between exposure and outcome), but this association is at best very small and potentially clinically not important. I also demonstrated that higher neighbourhood walkability is not associated with higher overall physical activity (the arguably more salient outcome for health) in adults with type 2 diabetes.

What does a more walkable neighbourhood look like?

To give readers a deeper understanding of the comparisons that were made in my doctoral studies, providing images of what a typical high and a typical low walkable neighbourhood looks like is useful. In Figure 9.2, I contrast two Montreal neighbourhoods with GIS-derived walkability scores differing by one standard deviation (i.e., the comparison made in *Manuscript 6*). The more walkable neighbourhood (Neighbourhood A) is characterized by multi-unit housing, a gridded street pattern, and closer proximity to stores and amenities. The less walkable neighbourhood (Neighbourhood B), has less connected streets, is composed of single unit housing, and is further from stores and other amenities. Although higher walkability did not translate into higher overall levels of physical activity in my sixth study, adults with type 2 diabetes who lived in high compared to low walkable neighbourhoods (e.g., Neighbourhood A *versus* Neighbourhood B) achieved approximately 165 more steps/day (95% CI 19, 312) within their home neighbourhoods. Images of neighbourhoods by quartiles of neighbourhood walkability (as analysed in *Manuscript 5*) are provided in Figure 9.3.

Figure 9.2 Two Montreal neighbourhoods with GIS-derived walkability scores differing by one standard deviation. Neighbourhood A is more walkable than Neighbourhood B. (Images taken from *www.google.ca/maps*)

Figure 9.3 Examples of Montreal neighbourhoods by quartile of GIS-derived neighbourhood walkability (Images taken from *www.google.ca/maps*)

Specific Substantive Contributions

Manuscript 1

- Six quantitative research articles were published prior to May 2014 on the association between neighbourhood walkability (based on GIS-derived measures of street connectivity, land use mix and/or population/residential density) and biosensor-assessed daily steps in adults.

- The results of four of these (2 Belgian studies, 1 Czech study, 1 Japanese study) could be pooled in a meta-analysis

- Adults who lived in high compared to low walkable neighbourhoods accumulated 766 more steps per day (95% CrI 250, 1271)

- There is a need for comparable studies to be conducted in Canada.

Manuscript 2

- The correlation between GIS-derived and audit-based neighbourhood walkability is high:
    - R: 0.7, 95% CI 0.6, 0.80

- The correlations of GIS-derived and audit-based neighbourhood walkability with participant-reported measures of neighbourhood walkability are low, suggesting that objective measures capture a different construct of neighbourhood walkability than perceived/participant-reported measures
    - Audit *versus* participant-reported: R: 0.2, 95% CI 0.06, 0.3
    - GIS-derived *versus* participant-reported: R: 0.2, 95% CI 0.04, 0.3

- GIS-derived measures appear to perform well in place of an in-field audit

Manuscript 3

- I demonstrated that using a variable rather than a constant definition of N in the Shannon entropy formula – a formula commonly used in the neighbourhoods and health literature to capture land use mix – may lead to a systematic underestimation of the true association by 26.4% (95% CI 25.8, 27.0)

- Given evidence that this formula has been misspecified by researchers, I encouraged researchers to use this formula with caution

Manuscript 4

- In Canadian adults, there was no association between GIS-derived neighbourhood walkability and accelerometer-assessed daily steps.

- Participants who reported more utilitarian walking accumulated more steps:
    - <1 hours/week: 6613 steps/day, 95% CI 6251, 6975
    - 1 to 5 hours/week: 6768 steps/day, 95% CI 6420, 7117
    - ≥6 hours/week: 7391 steps/day, 95% CI 6972, 7811

- There was a positive graded association between walkability and odds of walking ≥1 hour/week for utilitarian purposes independent of age, sex, body mass index, married/common-law status, annual household income, having children in the household, immigrant status, mood disorder, perceived health, ever smoker, and season.

GIS-derived walkability

  - Q2 *versus* Q1: OR:1.13, 95% CI 0.91, 1.39
  - Q3 *versus* Q1: OR: 1.41, 95% CI 1.14, 1.76
  - Q4 *versus* Q1: OR: 1.66, 95% CI 1.31, 2.11

Walk Score®

  - Q2 *versus* Q1: OR: 1.09, 95% CI 0.88, 1.35
  - Q3 *versus* Q1: OR: 1.70, 95% CI 1.36, 2.12
  - Q4 *versus* Q1: OR: 2.00, 95% CI 1.57, 2.54

Manuscript 5

- Adults with type 2 diabetes living in the highest compared to the lowest quartile of neighbourhood walkability achieved 606 more steps/day (Q4 *versus* Q1: 95% CrI 8, 1203) independent of age, sex, BMI, depressed mood, dog ownership, insulin use, immigrant status, season, and participant-reported walkability. The difference in steps between the second and first quartiles was similar in magnitude (Q2 *versus* Q1: 783 more steps/day, 95% CrI 168, 1406). These associations were, however, inconclusive and not graded across quartiles.

- No important associations with daily steps were observed for audit-assessed walkability or the Walk Score®.

- I did not have data on utilitarian walking in this study, but I did have access to participant-reported measures of neighbourhood walkability. Based on my analyses in *Manuscript 2*, I found that the correlation between GIS-derived walkability and participant-reported walkability was low. This led me to hypothesize that perhaps perceptions of neighbourhood walkability rather than objective measures of walkability are associated with higher levels of walking. Indeed, this is what I found. Those adults with type 2 diabetes who reported living in the most compared to the least walkable neighbourhoods (Quartiles 4 *versus* 1) completed 1345 more steps/day (95% CrI 718, 1976).

- I identified several important individual-level predictors of higher daily steps including age, BMI, depressed mood, dog ownership and season:
    - Age (every one-year decrement): 106 more steps/day, 95% CrI 85, 127)
    - BMI (every one-year decrement): 119 more steps/day, 95% CrI 82, 155)
    - Absence of depressed mood: 553 more steps/day, 95% CrI 90, 1023)
    - Dog owners (*versus* non-dog owners): 646 more steps/day, 95% CrI 28, 1250)
    - Summer/spring (*versus* fall/winter) season: 692 steps/day, 95% CrI 283, 1106)

Manuscript 6

- There was no association between neighbourhood walkability and the overall amount of physical activity (i.e., physical activity accumulated in all locations) that adults with type 2 diabetes achieve.
- In adults with type 2 diabetes, there is a very small positive association between neighbourhood walkability and neighbourhood-based physical activity after adjustment for age, body mass index, sex, university education, season, car access, residential self-selection, and wear-time: a one standard deviation increment in walkability was

associated with 10.4% of a SD increment in neighbourhood-based physical activity (95% CI 1.2, 19.7). Assuming that daily steps can be predicted from VeDBA, this is equivalent to a difference of 165 more steps/day (95% CI 19, 312) in residents of high versus low walkable neighbourhoods (i.e., neighbourhoods with a one SD deviation difference in the walkability score).

- 74% of the cohort had regular car access
- Not having regular car access was the strongest predictor of higher levels of neighbourhood-based physical activity:
    - Not having car access was associated with 38.6% of a SD increment in neighbourhood-based physical activity (95% CI 17.9, 59.3).
    - Assuming that daily steps can be predicted from VeDBA, participants who had access to a car accumulated 613 fewer steps per day within their residential neighbourhoods (95% CI -942, -284) than participants who did not have a car.
- Car access was not conclusively associated with overall levels of physical activity

Summary

While in Europe and Japan adults who live in highly walkable neighbourhoods walk more overall than adults living in low walkable neighbourhoods (*Manuscript 1*), my doctoral work demonstrates that there is no obvious association between neighbourhood walkability and total walking/total physical activity in the Canadian context. This was demonstrated in a large study of Canadian adults (*Manuscript 4*), and in two clinical studies of adults with type 2 diabetes (*Manuscripts 5 and 6*). It should be noted that the association for GIS-derived neighbourhood walkability in *Manuscript 5* was inconclusive (i.e., there were positive effect estimates in

Quartiles 2 and 4 but the confidence intervals were wide). However, given the lack of associations for the other researcher-assessed measures of walkability (i.e., audit-assessed walkability and the Walk Score®) in *Manuscript 5* and the lack of any association for GIS-derived walkability in *Manuscript 6,* it is likely that these associations would be null or clinically unimportant. Interestingly, when creating a precise spatial match between exposures and outcomes, I demonstrated that there is a small positive association between neighbourhood walkability and physical activity occurring specifically inside of the home neighbourhood but excluding the home (*Manuscript 6*).

Individual-level factors are more unequivocally associated with the total walking/total physical activity. In all three of my substantive studies (*Manuscripts 4, 5* and *6*), I identified numerous individual-level correlates of higher levels of total walking, including age, BMI, depressed mood, dog ownership, season, perceived neighbourhood walkability, and car access. Leveraging these factors (e.g., encouraging dog walking or promoting the walkable aspects of neighbourhoods) may be the most effective means by which to achieve population-level increases in total walking.

Strengths and Limitations

The specific limitations of my studies are described in the body of each manuscript. Here I outline only the key limitations of my doctoral research:

1. Given the cross-sectional nature of my studies, I could not draw conclusions regarding causality or the directionality of my observed relationships. Randomized control trials are needed to adequately assess causality. This would require researchers to move

participants into different types of neighbourhoods and to track changes in their levels of physical activity over time. This is not feasible for practical reasons (e.g., cost).

2. There is a possibility of unmeasured confounding. For example, in *Manuscript 4* I did not have any data on car access and residential selection - two variables that I identified as potential confounders based on the literature and based on the analyses that I did in *Manuscript 6*. For *Manuscript 5* I used data that had been collected in 2006-2008 and therefore did not have control over what data were collected. To address a lack of data on car access and residential self-selection, I conducted a follow-up survey in 2012/2013. In this survey I asked participants retrospectively about their car access and reasons for moving to their neighbourhoods. A fraction of participants returned completed surveys (n=56/201). To retain a maximal sample size, I did not include these two potential confounders in my final models. When I did include them part of my exploratory analyses, they did not lead to important changes in my conclusions. Further, since perfect measurement of variables is not possible, the presence of some residual confounding cannot be excluded.

3. Selection bias is a possibility in all of my substantive studies. Even though the data that I used in *Manuscript 4* was based on data collected by a nationally representative health survey, the people who agreed to participate in this survey are likely to represent the more motivated and perhaps ‘healthier’ segments of the population. The same applies for those adults with type 2 diabetes who agreed to participate in my latter two studies (*Manuscript 5* and *6*). If these individuals are indeed more motivated to engage in regular

physical activity, it is possible that neighbourhood walkability may have been less of a barrier for walking. Stronger associations may have emerged had more unmotivated segments of the population been included.

Despite these limitations, my thesis makes important contributions to our understanding of the role of neighbourhood walkability on total walking/total physical activity in Canadian adults. The major strengths of my doctoral research include:

1. Use of complementary methods of neighbourhood walkability assessments, including GIS-derived measures, in-field audits, perceived/participants reported measures, and real-time spatial and physical activity monitoring. Previous studies tend to rely on only one measure of walkability. Given that neighbourhood walkability is a multi-dimensional variable that can influence behaviours at multiple levels, use of complementary measures allowed me to glean a more comprehensive understanding of how neighbourhood designs influence the physical activity behaviours of adults.

2. Use of biosensor-assessed metrics of physical activity. The majority of previous studies on the walkability-total physical activity relationship have relied on self-reported measures of physical activity. Through the use of more objective measures of physical activity, I was able to avoid biases avoided with self-reports.

3. Use of a large population-based sample of Canadian adults from a wide range of neighbourhoods from across Canada (*Manuscripts 4*) increased variability in

neighbourhood walkability and thereby also increased my ability to detect important associations if they did exist.

4. Use of a clinical sample of adults with type 2 diabetes (*Manuscripts 5* and *6*). Adults with type 2 diabetes represent a population that may be particularly sensitive to features of their neighbourhood environments yet research regarding the role of environmental influences on health is limited in this population.

Major Future Research Directions

My research demonstrates that higher neighbourhood walkability is associated with higher levels of total walking in Europe and in Japan. Based on the studies that I conducted, however, there is no obvious association between neighbourhood walkability and total walking/total physical activity in the Canadian context. Although I demonstrated that neighbourhood walkability is positively associated with self-reported utilitarian walking and with small increases in physical activity inside of home neighbourhoods (areas we might expect to see influences of neighbourhood walkability via increased presence of transit stops or services/amenities, for example), the results of my doctoral research do not suggest that improving neighbourhood walkability would facilitate meaningful increases in total waking/total physical activity. Other factors will need to be leveraged instead.

Some important opportunities for facilitating increases in total levels of physical activity that I identified in my research include reducing seasonal deficits in walking (e.g., encouraging walking in the fall/winter months with careful attention to safety during months when risk of falls/fractures is high[234]), encouraging dog walking among dog owners, and improving perceptions of neighbourhood walkability (e.g., public promotion of the walkable features of neighbourhoods). I also demonstrated that reducing reliance on cars may be an effective means by which to increase levels of neighbourhood-based physical activity.

Although more research will need to be conducted in this area, it is possible that by reducing reliance on cars we may make adults more sensitive to the walkable features of their neighbourhood environments. Indeed, this may explain why neighbourhood walkability seems to matter in Europe and Asia, but not in Canada where car ownership is high. While car use is, in part, an individual-level choice, the decision to use a car is largely driven by factors that are directly related to the urban context (e.g., costs of driving a car may be less than costs of public transport, lack of public transit, cars are made to be affordable for middle class individuals). Before researchers and policy makers advise people to reduce their reliance on cars, cities must be made walking and public transit-friendly. How to best develop walking friendly and public transit-oriented cities represents an important line for future research. This is particularly true in light of an aging population. Designing communities that encourage active and health living in all segments of the population, including in older Canadians and those living with chronic diseases, is needed.

Another important area for future research is determining which policy investments produce the most active populations. Leveraging neighbourhood walkability appears to be only a small piece of the puzzle in making environments more favourable for active living (e.g., through increases in utilitarian walking), but it is not the magic bullet for facilitating increases in total physical activity. Multifaceted interventions that acknowledge the role of factors operating at multiple levels are needed. We are in an opportune time to start asking and answering big picture questions such as *"Do governments that make large investments in the creation of active* *transportation-oriented communities achieve population-level increases in physical activity?"* and to make large strides forwards in the creation of healthy and sustainable communities. On October 19, 2015 the Liberal Party of Canada was elected to power under the leadership of Justin Trudeau. As part of their platform, the Liberal Party promised to quadruple federal investment into public transportation over the next decade by investing nearly $20 billion CAD in transit infrastructure in communities all across the country.[235] Given the impending government-sponsored public transit-oriented investments that will be made in the next ten years, now is the time for urban planners, health professionals, and governmental stakeholders to begin evaluating the benefits of these interventions. As an example, in celebration of the 375th year anniversary of the City of Montreal, plans are underway to create a 3.8 km walking path that will connect Mount Royal, the focal point of Montreal, to the St. Lawrence River.[236] The goal of the project (La Promenade Fleuve-Montagne) is to encourage walking among residents and visitors and presents an excellent opportunity for the study of pre-post intervention effects.

In addition to understanding the benefits of government-sponsored investments on public transit and active commuting, there is also a need for research on understanding how 'new' technologies (e.g., telecommunting, online university courses and internet grocery delivery systems) might dampen the effects of interventions aimed at increasing levels of physical activity. For example, a city may become equipped with a highly efficient public transit system, but if people are accustomed to using their cars and are unwilling to change their habits, this transit system will be of no benefit. We are at the beginning of an exciting time of understanding how environments influence health. By addressing these large-scale multifactorial issues, we will begin to understand how best to facilitate increases in physical activity.

Closing Remarks

Through my doctoral research I demonstrated that, in Europe and Japan, adults who live in more walkable neighbourhoods walk more than adults who live in less walkable neighbourhoods. In contrast, I demonstrated that there is no obvious association between neighbourhood walkability and total walking/total physical among Canadian adults living with or without type 2 diabetes. This suggests that leveraging neighbourhood walkability (based on street connectivity, land use mix and residential/population density) may not be effective in facilitating increases in total physical activity among Canadian adults. Instead, targeting individual-level predictors of total physical activity (in the presence of supportive environments) may hold greater benefits.

The well-known epidemiologist Geoffrey Rose proposed a population-wide approach for preventive medicine in his seminal 1985 piece titled *Sick Individuals and Sick Populations.*[237] Rose suggested that the most effective way to reduce the burden of disease (e.g., physical inactivity) is by targeting distal risk factors that affect large segments of the population (e.g., neighbourhood walkability) rather than by focusing on individuals at high-risk alone.[237] In the context of the neighbourhoods and health literature, however, it appears that interventions will need to target both environments and individuals in order to achieve population-level increases in total walking. For example, it would be futile to encourage people to walk to work or to commute using public transit without providing safe walking paths or cost-beneficial public travel options. Similarly, building safe walking paths and public transit systems might only encourage more walking in highly motivated individuals unless they are coupled with strategies that make walking to work/public transit appealing to the majority of people (e.g., advertising the benefits of walking and the walkable features of neighbourhoods).

In order for the medical and public health communities to help facilitate population-level increases in physical activity, interventions that target multiple determinants of physical activity are needed. The design of multifactorial interventions will require buy-in from key stakeholders and may take years to implement. Nevertheless, there is hope. Just as the age of the automobile in 1945 brought with it the American dream of owning a car and a home in the suburbs (See Figure 1.2, Chapter 1, page 2), there is evidence that the public is beginning to understand the importance of physical activity and active travel is once again being promoted (Figure 9.4). Now is the time for clinicians, public health officials, media partners, and the public alike to join forces and unreservedly promote active living across the lifespan.

Figure ***9.4*** Recent advertisements promoting active transport (Images taken from *www.functionhealthclub.com*, *www.waba.org*, and *www.infographics.idlelist.com*)

REFERENCES

1. Crawford JH. *Carfree Design Manual.* Utrecht, Netherlands: International Books; 2009.
2. Badland H. Transport, urban design, and physical activity: an evidence-based update. *Transportation Research Part D* 2005;10:177-196.
3. Frumkin H, Frank L, Jackson R. *Urban sprawl and public health: Designing, planning, and building for healthy communities.* Washington, DC: Island Press; 2004.
4. Frank L, Engelke P, Schmid T. *Health and community design.* 1718 Connecticut Avenue, NW, Suite 300, Washington, DC: Island Press; 2003.
5. Newman P. Walking in a historical, international and contemporary context. In: Tolley R, ed. *Sustainable trasnport: Planning for walking and cycling in urban envionments*. Abington Hall, Abington; Cambridge, England: Woodhead Publishing Limited; 2003:48-58.
6. Frank L. Land use and transportation interaction: Implications on public health and quality of life. *Jouranl of Planning Education and Research.* 2000;20:6-22.
7. Fisher JE. Transportation Modes and Challenges to Sustainability: A historical Perspective. *ITE Journal.* 2010;80(3):16-18.
8. Thurston RH. *A History of the Growth of the Steam-Engine.* Vol XXIV. 1 Patterson Square, London: Kegan Paul, Trench & Co.; 1887.
9. The consumer economy and mass entertainment. 2016; http://www.digitalhistory.uh.edu/disp_textbook.cfm?smtID=2&psid=3396. Accessed March 14, 2016.
10. Foster M. *A nation on wheels: The automobile culture in America since 1945.* Belmont, MA: Thomson Learning; 2003.

11. Speck J. *Walkable City: How downtown can save North America, one step at a time.* New York: Farrar, Straus and Giroux; 2012.

12. Chinmoy S, Webster C, Gallacher J. *Healthy cities: Public planning though urban planning.* Northampton, Massachusetts: Edward Elgar Publishing Inc.; 2014.

13. Statistics Canada. Canada's population estimates: Subprovincial areas. July 1, 2014.

14. Stein CS. *Toward New Towns for America.* New York: Reinhold Publishing Corporation; 1957.

15. Patricios NN. Urban design principles of the original neighbourhood concepts. *Urban Morphology.* 2002;6(1):21-32.

16. Brownson RC, Boehmer TK, Luke DA. Declining rates of physical activity in the United States: what are the contributors? *Annu Rev Public Health.* 2005;26:421-443.

17. French SA, Story M, Jeffery RW. Environmental influences on eating and physical activity. *Annu Rev Public Health.* 2001;22:309-335.

18. Handy SL, Cao X, Mokhtarian PL. Self-Selection in the Relationship between the Built Environment and Walking. *Journal of the American Planning Association.* 2006;72(1).

19. Bandura A. The self system in reciprocal determinism. *American Psychologist.* 1978.

20. Prochaska JO, DiClemente CC. Stages and processes of self-change of smoking: toward an integrative model of change. *J Consult Clin Psychol.* 1983;51(3):390-395.

21. Prochaska JO. Transtheoretical therapy: Toward a more integrative model of change. *Psychotherapy: Theory, Research and Practice.* 1982;19(3).

22. Li F, Fisher KJ, Bauman A, et al. Neighborhood influences on physical activity in middle-aged and older adults: a multilevel perspective. *J Aging Phys Act.* 2005;13(1):87-114.

23. De Greef K, Van Dyck D, Deforche B, De Bourdeaudhuij I. Physical environmental correlates of self-reported and objectively assessed physical activity in Belgian type 2 diabetes patients. *Health Soc Care Community.* 2011;19(2):178-188.

24. Bauman AE, Sallis JF, Dzewaltowski DA, Owen N. Toward a better understanding of the influences on physical activity: the role of determinants, correlates, causal variables, mediators, moderators, and confounders. *Am J Prev Med.* 2002;23(2 Suppl):5-14.

25. Donahue KE, Mielenz TJ, Sloane PD, Callahan LF, Devellis RF. Identifying supports and barriers to physical activity in patients at risk for diabetes. *Prev Chronic Dis.* 2006;3(4):A119.

26. Hays LM, Clark DO. Correlates of physical activity in a sample of older adults with type 2 diabetes. *Diabetes Care.* 1999;22(5):706-712.

27. Hall KS, McAuley E. Individual, social environmental and physical environmental barriers to achieving 10 000 steps per day among older women. *Health education research.* 2010;25(3):478-488.

28. McLeroy KR, Bibeau D, Steckler A, Glanz K. An ecological perspective on health promotion programs. *Health Educ Q.* 1988;15(4):351-377.

29. Sallis JF, Bauman A, Pratt M. Environmental and policy interventions to promote physical activity. *Am J Prev Med.* 1998;15(4):379-397.

30. King AC, Jeffery RW, Fridinger F, et al. Environmental and policy approaches to cardiovascular disease prevention through physical activity: issues and opportunities. *Health Educ Q.* 1995;22(4):499-511.

31. Berrigan D, McKinnon RA. Built environment and health. *Prev Med.* 2008;47(3):239-240.

32. Humpel N, Owen N, Leslie E. Environmental factors associated with adults' participation in physical activity: a review. *Am J Prev Med.* 2002;22(3):188-199.

33. Plotnikoff RC, Trinh L, Courneya KS, Karunamuni N, Sigal RJ. Predictors of physical activity in adults with type 2 diabetes. *Am J Health Behav.* 2011;35(3):359-370.

34. Deshpande AD, Baker EA, Lovegreen SL, Brownson RC. Environmental correlates of physical activity among individuals with diabetes in the rural midwest. *Diabetes Care.* 2005;28(5):1012-1018.

35. Cervero R. Travel demand and the 3Ds: Density, diversity, and design. *Transpn Res.* 1997;2(3):199-219.

36. Smith KR, Brown BB, Yamada I, Kowaleski-Jones L, Zick CD, Fan JX. Walkability and body mass index density, design, and new diversity measures. *Am J Prev Med.* 2008;35(3):237-244.

37. Leslie E, Coffee N, Frank L, Owen N, Bauman A, Hugo G. Walkability of local communities: using geographic information systems to objectively assess relevant environmental attributes. *Health Place.* 2007;13(1):111-122.

38. Saelens BE, Sallis JF, Frank LD. Environmental correlates of walking and cycling: findings from the transportation, urban design, and planning literatures. *Ann Behav Med.* 2003;25(2):80-91.

39. Frank LD, Saelens BE, Powell KE, Chapman JE. Stepping towards causation: do built environments or neighborhood and travel preferences explain physical activity, driving, and obesity? *Soc Sci Med.* 2007;65(9):1898-1914.

40. Ewing R, Cervero R. Travel and the built environment: A meta-analysis. *Journal of the American Planning Association.* 2010;76(3).

41. Frank LD, Schmid TL, Sallis JF, Chapman J, Saelens BE. Linking objectively measured physical activity with objectively measured urban form: findings from SMARTRAQ. *Am J Prev Med.* 2005;28(2 Suppl 2):117-125.

42. Saelens BE, Sallis JF, Black JB, Chen D. Neighborhood-based differences in physical activity: an environment scale evaluation. *Am J Public Health.* 2003;93(9):1552-1558.

43. Saelens BE, Sallis JF, Frank L. Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures. *Annals of Behavioural Medicine.* 2003;25(2):80-91.

44. Manaugh K, Kreider T. What is mixed use? Presenting an interaction method for measuring land use mix. *The Journal of Transport and Land Use.* 2013;6(1):63-72.

45. Saelens BE, Sallis JF, Black JB, Chen D. Neighborhood-based differences in physical activity: an environment scale evaluation. *Am J Public Health.* 2003;93(9):1552-1558.

46. Clifton K, Livi A, Rodriguez DA. Pedestrian Environment Data Scan (PEDS) Tool. In: Growth NCfS, ed. College Park: University of Maryland; 2004.

47. Cain KL, Millstein RA, Sallis JF, et al. Contribution of streetscape audits to explanation of physical activity in four age groups based on the Microscale Audit of Pedestrian Streetscapes (MAPS). *Soc Sci Med.* 2014;116:82-92.

48. Brownson RC, Brennan-Ramirez LK, Hoehner CM, Cook RA. Analytic Audit Tool and Checklist Audit Tool. Saint Louis University School of Public Health2003.

49. Rundle AG, Bader MD, Richards CA, Neckerman KM, Teitler JO. Using Google Street View to audit neighborhood environments. *Am J Prev Med.* 2011;40(1):94-100.

50. Clarke P, Ailshire J, Melendez R, Bader M, Morenoff J. Using Google Earth to conduct a neighborhood audit: reliability of a virtual audit instrument. *Health Place.* 2010;16(6):1224-1229.

51. Badland HM, Opit S, Witten K, Kearns RA, Mavoa S. Can virtual streetscape audits reliably replace physical streetscape audits? *J Urban Health.* 2010;87(6):1007-1016.

52. Gullon P, Badland HM, Alfayate S, et al. Assessing Walking and Cycling Environments in the Streets of Madrid: Comparing On-Field and Virtual Audits. *J Urban Health.* 2015;92(5):923-939.

53. Tomlinson R, Toomey MAG. GIS and LIS in Canada. In: McGrath G, Sebert L, eds. *Mapping a Northern Land: The Survey of Canada, 1947-1994*: McGill-Queen's University Press; 1999.

54. McLafferty SL. GIS and health care. *Annu Rev Public Health.* 2003;24:25-42.

55. Croner CM. Public health, GIS, and the internet. *Annu Rev Public Health.* 2003;24:57-82.

56. National Geographic. Encyclopedic Entry: GIS (Geographic Information System). http://education.nationalgeographic.com/encyclopedia/geographic-information-system-gis/, 2015.

57. Oliver LN, Schuurman N, Hall AW. Comparing circular and network buffers to examine the influence of land use on walking for leisure and errands. *Int J Health Geogr.* 2007;6:41.

58. Frank LD, Schmid TL, Sallis JF, Chapman J, Saelens BE. Linking objectively measured physical activity with objectively measured urban form: findings from SMARTRAQ. *Am J Prev Med.* 2005;28(2 Suppl 2):117-125.

59. Oliver LN, Schuurman N, Hall AW. Comparing circular and network buffers to examine the influence of land use on walking for leisure and errands. *Int J Health Geogr.* 2007;6:41.

60. Villanueva K, Knuiman M, Nathan A, et al. The impact of neighborhood walkability on walking: does it differ across adult life stage and does neighborhood buffer size matter? *Health Place.* 2014;25:43-46.

61. Tuckel P, Milczarski W. Walk Score(TM), Perceived Neighborhood Walkability, and walking in the US. *Am J Health Behav.* 2015;39(2):242-256.

62. Hirsch JA, Moore KA, Evenson KR, Rodriguez DA, Diez Roux AV. Walk Score(R) and Transit Score(R) and walking in the multi-ethnic study of atherosclerosis. *Am J Prev Med.* 2013;45(2):158-166.

63. Brown SC, Pantin H, Lombard J, et al. Walk Score(R): associations with purposive walking in recent Cuban immigrants. *Am J Prev Med.* 2013;45(2):202-206.

64. Takahashi PY, Baker MA, Cha S, Targonski PV. A cross-sectional survey of the relationship between walking, biking, and the built environment for adults aged over 70 years. *Risk Manag Healthc Policy.* 2012;5:35-41.

65. Carr LJ, Dunsiger SI, Marcus BH. Validation of Walk Score for estimating access to walkable amenities. *Br J Sports Med.* 2011;45(14):1144-1148.

66. Carr LJ, Dunsiger SI, Marcus BH. Walk score as a global estimate of neighborhood walkability. *Am J Prev Med.* 2010;39(5):460-463.

67. Duncan DT. What's your Walk Score(R)?: Web-based neighborhood walkability assessment for health promotion and disease prevention. *Am J Prev Med.* 2013;45(2):244-245.

68. Carr LJ, Dunsiger SI, Marcus BH. Walk Score™ as a global estimate of neighborhood walkability. *American journal of preventive medicine.* 2010;39(5):460-463.

69. Leslie E, Coffee N, Frank L, Owen N, Bauman A, Hugo G. Walkability of local communities: using geographic information systems to objectively assess relevant environmental attributes. *Health Place.* 2007;13(1):111-122.

70. Walk Score Methodology. 2015; https://www.walkscore.com/methodology.shtml. Accessed October 4, 2015.

71. Lerner M. 2014 City and Neighborhood Ranking Methodology. 2013; http://blog.walkscore.com/2013/11/2014-rankings-methodology/ - .VuYJEIuCxUQ. Accessed March 15, 2016.

72. Chiu M, Shah BR, Maclagan LC, Rezai MR, Austin PC, Tu JV. Walk Score(R) and the prevalence of utilitarian walking and obesity among Ontario adults: A cross-sectional study. *Health Rep.* 2015;26(7):3-10.

73. Glazier RH, Creatore MI, Weyman JT, et al. Density, destinations or both? A comparison of measures of walkability in relation to transportation behaviors, obesity and diabetes in Toronto, Canada. *PLoS One.* 2014;9(1):e85295.

74. Smith KR, Brown BB, Yamada I, Kowaleski-Jones L, Zick CD, Fan JX. Walkability and body mass index density, design, and new diversity measures. *Am J Prev Med.* 2008;35(3):237-244.

75. Auchincloss AH, Diez Roux AV, Brown DG, Erdmann CA, Bertoni AG. Neighborhood resources for physical activity and healthy foods and their association with insulin resistance. *Epidemiology.* 2008;19(1):146-157.

76. Hsieh S, Klassen AC, Curriero FC, et al. Fast-food restaurants, park access, and insulin resistance among Hispanic youth. *Am J Prev Med.* 2014;46(4):378-387.

77. Booth GL, Creatore MI, Moineddin R, et al. Unwalkable neighborhoods, poverty, and the risk of diabetes among recent immigrants to Canada compared with long-term residents. *Diabetes Care.* 2013;36(2):302-308.

78. Sundquist K, Eriksson U, Mezuk B, Ohlsson H. Neighborhood walkability, deprivation and incidence of type 2 diabetes: a population-based study on 512,061 Swedish adults. *Health Place.* 2015;31:24-30.

79. Kruger J, Ham SA, Berrigan D, Ballard-Barbash R. Prevalence of transportation and leisure walking among U.S. adults. *Prev Med.* 2008;47(3):329-334.

80. Owen N, Humpel N, Leslie E, Bauman A, Sallis JF. Understanding environmental influences on walking; Review and research agenda. *Am J Prev Med.* 2004;27(1):67-76.

81. Grasser G, Van Dyck D, Titze S, Stronegger W. Objectively measured walkability and active transport and weight-related outcomes in adults: a systematic review. *Int J Public Health.* 2013;58(4):615-625.

82. Saelens BE, Handy SL. Built environment correlates of walking: a review. *Med Sci Sports Exerc.* 2008;40(7 Suppl):S550-566.

83. Thielman J, Rosella L, Copes R, Lebenbaum M, Manson H. Neighborhood walkability: Differential associations with self-reported transport walking and leisure-time physical activity in Canadian towns and cities of all sizes. *Prev Med.* 2015;77:174-180.

84. Oakes JM, Forsyth A, Schmitz KH. The effects of neighborhood density and street connectivity on walking behavior: the Twin Cities walking study. *Epidemiol Perspect Innov.* 2007;4:16.

85. Gauvin L, Riva M, Barnett T, et al. Association between neighborhood active living potential and walking. *Am J Epidemiol.* 2008;167(8):944-953.

86. Hajna S, Ross NA, Brazeau A, Bélisle P, Joseph L, Dasgupta K. Associations between neighbourhood walkability and daily steps in adults: A systematic review and meta-analysis. *BMC Public Health.* 2015;In Press.

87. Miyazaki R, Kotani K, Tsuzaki K, Sakane N, Yonei Y, Ishii K. Effects of a year-long pedometer-based walking program on cardiovascular disease risk factors in active older people. *Asia Pac J Public Health.* 2015;27(2):155-163.

88. Pillay JD, van der Ploeg HP, Kolbe-Alexander TL, et al. The association between daily steps and health, and the mediating role of body composition: a pedometer-based, cross-sectional study in an employed South African population. *BMC Public Health.* 2015;15:174.

89. Pillay JD, Kolbe-Alexander TL, van Mechelen W, Lambert EV. Steps that count: the association between the number and intensity of steps accumulated and fitness and health measures. *J Phys Act Health.* 2014;11(1):10-17.

90. Gonzales JU. Do older adults with higher daily ambulatory activity have lower central blood pressure? *Aging Clin Exp Res.* 2015.

91. Kannel WB. Role of blood pressure in cardiovascular morbidity and mortality. *Prog Cardiovasc Dis.* 1974;17(1):5-24.

92. Lewington S, Clarke R, Qizilbash N, Peto R, Collins R, Prospective Studies C. Age-specific relevance of usual blood pressure to vascular mortality: a meta-analysis of individual data for one million adults in 61 prospective studies. *Lancet.* 2002;360(9349):1903-1913.

93. Kannel WB. Risk stratification in hypertension: new insights from the Framingham Study. *Am J Hypertens.* 2000;13(1 Pt 2):3S-10S.

94. Prospective Studies C, Whitlock G, Lewington S, et al. Body-mass index and cause-specific mortality in 900 000 adults: collaborative analyses of 57 prospective studies. *Lancet.* 2009;373(9669):1083-1096.

95. Smith TC, Wingard DL, Smith B, Kritz-Silverstein D, Barrett-Connor E. Walking decreased risk of cardiovascular disease mortality in older adults with diabetes. *J Clin Epidemiol.* 2007;60(3):309-317.

96. Kannel WB, McGee DL. Diabetes and cardiovascular disease. The Framingham study. *Jama.* 1979;241(19):2035-2038.

97. Schondorf T, Lubben G, Karagiannis E, Erdmann E, Forst T, Pfutzner A. Increased prevalence of cardiovascular disease and risk biomarkers in patients with unknown type 2 diabetes visiting cardiology specialists: results from the DIASPORA study. *Diabetes & vascular disease research : official journal of the International Society of Diabetes and Vascular Disease.* 2010;7(2):145-150.

98. Public Health Agency of Canada. What can happen if I have uncontrolled high blood pressure and what can I do to lower it. 2009; http://www.phac-aspc.gc.ca.

99. Tudor-Locke CE, Bell RC, Myers AM, Harris SB, Lauzon N, Rodger NW. Pedometer-determined ambulatory activity in individuals with type 2 diabetes. *Diabetes research and clinical practice.* 2002;55(3):191-199.

100. Van Vrancken C, Bopp CM, Reis JP, DuBose KD, Kirtland KA, Ainsworth BE. The prevalence of leisure-time physical activity among diabetics in South Carolina. *South Med J.* 2004;97(2):141-144.

101. Yates T, Haffner SM, Schulte PJ, et al. Association between change in daily ambulatory activity and cardiovascular events in people with impaired glucose tolerance (NAVIGATOR trial): a cohort analysis. *Lancet.* 2013.

102. Gregg EW, Gerzoff RB, Caspersen CJ, Williamson DF, Narayan KM. Relationship of walking to mortality among US adults with diabetes. *Arch Intern Med.* 2003;163(12):1440-1447.

103. van Poppel MN, Chinapaw MJ, Mokkink LB, van Mechelen W, Terwee CB. Physical activity questionnaires for adults: a systematic review of measurement properties. *Sports Med.* 2010;40(7):565-600.

104. Friedenreich CM, Courneya KS, Neilson HK, et al. Reliability and validity of the Past Year Total Physical Activity Questionnaire. *Am J Epidemiol.* 2006;163(10):959-970.

105. Chu AH, Ng SH, Koh D, Muller-Riemenschneider F. Reliability and Validity of the Self- and Interviewer-Administered Versions of the Global Physical Activity Questionnaire (GPAQ). *PLoS One.* 2015;10(9):e0136944.

106. Garriguet D, Tremblay S, Colley RC. Comparison of Physical Activity Adult Questionnaire results with accelerometer data. *Health Rep.* 2015;26(7):11-17.

107. Craig CL, Marshall AL, Sjostrom M, et al. International physical activity questionnaire: 12-country reliability and validity. *Med Sci Sports Exerc.* 2003;35(8):1381-1395.

108. Adams SA, Matthews CE, Ebbeling CB, et al. The effect of social desirability and social approval on self-reports of physical activity. *Am J Epidemiol.* 2005;161(4):389-398.

109. Prince SA, Adamo KB, Hamel ME, Hardt J, Connor Gorber S, Tremblay M. A comparison of direct versus self-report measures for assessing physical activity in adults: a systematic review. *Int J Behav Nutr Phys Act.* 2008;5:56.

110. Sallis JF, Saelens BE. Assessment of physical activity by self-report: status, limitations, and future directions. *Res Q Exerc Sport.* 2000;71 Suppl 2:1-14.

111. Shephard RJ. Limits to the measurement of habitual physical activity by questionnaires. *Br J Sports Med.* 2003;37(3):197-206; discussion 206.

112. Lim S, Wyker B, Bartley K, Eisenhower D. Measurement error of self-reported physical activity levels in New York City: assessment and correction. *Am J Epidemiol.* 2015;181(9):648-655.

113. Tudor-Locke C, Williams JE, Reis JP, Pluto D. Utility of pedometers for assessing physical activity: convergent validity. *Sports Med.* 2002;32(12):795-808.

114. Esliger DW, Probert A, Connor Gorber S, Bryan S, Laviolette M, Tremblay MS. Validity of the Actical accelerometer step-count function. *Med Sci Sports Exerc.* 2007;39(7):1200-1204.

115. Tudor-Locke C, Bassett DR, Jr. How many steps/day are enough? Preliminary pedometer indices for public health. *Sports Med.* 2004;34(1):1-8.

116. A beginner's guide to accelerometers. *Robotics, radio control, power electronics* http://www.dimensionengineering.com/info/accelerometers. Accessed October 5, 2015, 2015.

117. Piezotronics P. Introduction to Piezoelectric Accelerometers. 2015; https://www.pcb.com/techsupport/tech_accel.aspx.

118. Zheng Y, Weng-Keen W, Guan X, Trost S. Physical Activity Recognition from Accelerometer Data Using a Multi-Scale Ensemble Method. Paper presented at: Twenty-Fifth Innovative Applications of Artificial Intelligence Conference2013.

119. Santos-Lozano A, Santin-Medeiros F, Cardon G, et al. Actigraph GT3X: validation and determination of physical activity intensity cut points. *Int J Sports Med.* 2013;34(11):975-982.

120. Aguilar-Farias N, Brown WJ, Peeters GM. ActiGraph GT3X+ cut-points for identifying sedentary behaviour in older adults in free-living environments. *J Sci Med Sport.* 2014;17(3):293-299.

121. Abel MG, Hannon JC, Sell K, Lillie T, Conlin G, Anderson D. Validation of the Kenz Lifecorder EX and ActiGraph GT1M accelerometers for walking and running in adults. *Appl Physiol Nutr Metab.* 2008;33(6):1155-1164.

122. WGT3X-BT MONITOR. 2015; http://www.actigraphcorp.com/products/wgt3x-bt-monitor/. Accessed October 4, 2015.

123. Tudor-Locke CE, Bell RC, Myers AM, Harris SB, Lauzon N, Rodger NW. Pedometer-determined ambulatory activity in individuals with type 2 diabetes. *Diabetes Res Clin Pract.* 2002;55(3):191-199.

124. Zhao N. Full-featured pedometer design realized with 3-axis digital accelerometer. *Analog Dialogue.* 2010;June:1-6.

125. Tudor-Locke C, Williams JE, Reis JP, Pluto D. Utility of pedometers for assessing physical activity: construct validity. *Sports Med.* 2004;34(5):281-291.

126. Schneider PL, Crouter S, Bassett DR. Pedometer measures of free-living physical activity: comparison of 13 models. *Med Sci Sports Exerc.* 2004;36(2):331-335.

127. Curry C. Fitness Trackers: Step by Step to Better Health or Driving Us Crazy? 2013. http://abcnews.go.com/Technology/fitness-trackers-step-step-health-driving-us-crazy/story?id=19936093.

128. Khan A. Easy Ways to Get 10,000 Steps Per Day. 2015. http://health.usnews.com/health-news/health-wellness/slideshows/easy-ways-to-get-10-000-steps-per-day.

129. Do you really need to take 10,000 steps a day to keep fit? 2015. http://www.bbc.com/news/magazine-33154510.

130. Tudor-Locke C, Hatano Y, Pangrazi RP, Kang M. Revisiting "how many steps are enough?". *Med Sci Sports Exerc.* 2008;40(7 Suppl):S537-543.

131. World Health Organization. Global Health Observatory: Prevalence of Insufficient Physical Activity. 2015; http://www.who.int/gho/ncd/risk_factors/physical_activity_text/en/index.html. Accessed February 17, 2015.

132. The World Bank Group. Worldwide Passenger Cars (per 1,000 people). 2007.

133. Korkiakangas EE, Alahuhta MA, Laitinen JH. Barriers to regular exercise among adults at high risk or diagnosed with type 2 diabetes: a systematic review. *Health Promot Int.* 2009;24(4):416-427.

134. Casey D, De Civita M, Dasgupta K. Understanding physical activity facilitators and barriers during and following a supervised exercise programme in Type 2 diabetes: a qualitative study. *Diabet Med.* 2010;27(1):79-84.

135. Huebschmann AG, Crane LA, Belansky ES, Scarbro S, Marshall JA, Regensteiner JG. Fear of injury with physical activity is greater in adults with diabetes than in adults without diabetes. *Diabetes Care.* 2011;34(8):1717-1722.

136. Taylor LM, Leslie E, Plotnikoff RC, Owen N, Spence JC. Associations of perceived community environmental attributes with walking in a population-based sample of adults

with type 2 diabetes. *Annals of behavioral medicine : a publication of the Society of Behavioral Medicine.* 2008;35(2):170-178.

137. Ford ES, Herman WH. Leisure-time physical activity patterns in the U.S. diabetic population. Findings from the 1990 National Health Interview Survey--Health Promotion and Disease Prevention Supplement. *Diabetes Care.* 1995;18(1):27-33.

138. Di Loreto C, Fanelli C, Lucidi P, et al. Make your diabetic patients walk: long-term impact of different amounts of physical activity on type 2 diabetes. *Diabetes care.* 2005;28(6):1295-1302.

139. Pescatello LS. Physical activity, cardiometabolic health and older adults: recent findings. *Sports medicine.* 1999;28(5):315-323.

140. Feskanich D, Willett W, Colditz G. Walking and leisure-time activity and risk of hip fracture in postmenopausal women. *JAMA : the journal of the American Medical Association.* 2002;288(18):2300-2306.

141. Thomas N, Alder E, Leese GP. Barriers to physical activity in patients with diabetes. *Postgraduate Medical Journal.* 2004;80.

142. Bracy NL, Millstein RA, Carlson JA, et al. Is the relationship between the built environment and physical activity moderated by perceptions of crime and safety? *Int J Behav Nutr Phys Act.* 2014;11(1):24.

143. King D. Neighborhood and individual factors in activity in older adults: results from the neighborhood and senior health study. *J Aging Phys Act.* 2008;16(2):144-170.

144. Hall KS, McAuley E. Individual, social environmental and physical environmental barriers to achieving 10 000 steps per day among older women. *Health Educ Res.* 2010;25(3):478-488.

145. Bentley R, Jolley D, Kavanagh AM. Local environments as determinants of walking in Melbourne, Australia. *Soc Sci Med.* 2010;70(11):1806-1815.

146. Cerin E, Cain KL, Conway TL, et al. Neighborhood environments and objectively measured physical activity in 11 countries. *Med Sci Sports Exerc.* 2014;46(12):2253-2264.

147. Cervero R, Gorham R. Commuting in Transit Versus Automobile Neighborhoods. *Journal of the American Planning Association.* 1995;61(2):210.

148. Trost SG, Owen N, Bauman AE, Sallis JF, Brown W. Correlates of adults' participation in physical activity: review and update. *Med Sci Sports Exerc.* 2002;34(12):1996-2001.

149. Saelens BE, Handy SL. Built environment correlates of walking: a review. *Med Sci Sports Exerc.* 2008;40(7 Suppl):S550-566.

150. Handy SL, Boarnet MG, Ewing R, Killingsworth RE. How the built environment affects physical activity: views from urban planning. *Am J Prev Med.* 2002;23(2 Suppl):64-73.

151. Saelens BE, Sallis JF, Frank LD. Environmental correlates of walking and cycling: findings from the transportation, urban design, and planning literatures. *Ann Behav Med.* 2003;25(2):80-91.

152. Sallis JF, Frank L, Saelens BE, Kraft MK. Active transportation and physical activity: opportunities for collaboration on transportation and public health research. *Transportation Research Part A.* 2004:249-268.

153. Tudor-Locke CE, Bell RC, Meyers AM. Revisiting the role of physical activity and exercise in the treatment of type 2 diabetes. *Can J Appl Physiol.* 2000;25(6):466-492.

154. Li F, Fisher KJ, Bauman A, et al. Neighborhood influences on physical activity in middle-aged and older adults: a multilevel perspective. *J Aging Phys Act.* 2005;13(1):87-114.

155. Eyler AA, Brownson RC, Bacak SJ, Housemann RA. The epidemiology of walking for physical activity in the United States. *Med Sci Sports Exerc.* 2003;35(9):1529-1536.

156. Holtzclaw J. Using residential patterns and transit to decrease auto dependence and costs. *Unpublished Manuscript.*New York: National Resources Defense Council.

157. Rice Centre. Houston’s Major Activity Centers and Worker Travel Behavior. In: Council RpftH-GA, ed1987.

158. Cervero R. Land-use mixing and suburban mobility. *Transportation Quarterly.* 1988;42(3):429-446.

159. Handy SL, Clifton K. Local shopping as a strategy for reduc- ing automobile travel. *Transportation.* 2001;28:317-346.

160. Handy SL. Urban form and pedestrian choices: Study of Austin neighborhoods. *Transportation Research Record.* 1996;1552:135-144.

161. Handy SL. Regional versus local accessibility: Neo-traditional development and its implications for non-work travel. *Built Environment.* 1992;18:253-267.

162. Sallis JF, Johnson MF, Calfas KJ, Caparosa S, Nichols JF. Assessing perceived physical environmental variables that may influence physical activity. *Res Q Exerc Sport.* 1997;68(4):345-351.

163. McCormack G, Giles-Corti B, Lange A, Smith T, Martin K, Pikora TJ. An update of recent evidence of the relationship between objective and self-report measures of the

physical environment and physical activity behaviours. *J Sci Med Sport.* 2004;7(1 Suppl):81-92.

164. Cunningham GO, Michael YL. Concepts guiding the study of the impact of the built environment on physical activity for older adults: a review of the literature. *Am J Health Promot.* 2004;18(6):435-443.

165. Duncan MJ, Spence JC, Mummery WK. Perceived environment and physical activity: a meta-analysis of selected environmental characteristics. *Int J Behav Nutr Phys Act.* 2005;2:11.

166. Cao X, Mokhtarian PL, Handy SL. Examining the impacts of residential self-selection on travel behaviour: Methodologies and empirical findings. *Summarized in two journal articles: 1) Cao, X, Mokhtarian, P. L. & Cao, X (2009) Examining the impacts of residential self-selection on travel behaviour: A focus on empirical findings. Transport Reviews. and 2) Mokhtarian, P. L. & Cao, X (2008) Examining the impacts of residential self-selection on travel behaviour: A focus on methodologies. Transportation Research B, 42 (3), 204-228.* 2008.

167. Cerin E, Saelens BE, Sallis JF, Frank LD. Neighborhood Environment Walkability Scale: validity and development of a short form. *Med Sci Sports Exerc.* 2006;38(9):1682-1691.

168. Boarnet MG, Day K, Alfonzo M, Forsyth A, Oakes M. The Irvine-Minnesota inventory to measure built environments: reliability tests. *Am J Prev Med.* 2006;30(2):153-159.

169. Day K, Boarnet M, Alfonzo M, Forsyth A. The Irvine-Minnesota inventory to measure built environments: development. *Am J Prev Med.* 2006;30(2):144-152.

170. Clifton K, Smith LA, Rodriguez D. The development and testing of an audit for the pedestrian environment. *Landscape and Urban Planning.* 2007;80:95-110.

171. Brownson RC, Hoehner CM, Day K, Forsyth A, Sallis JF. Measuring the built environment for physical activity: state of the science. *Am J Prev Med.* 2009;36(4 Suppl):S99-123 e112.

172. Talen E, Koschinsky J. The Walkable Neighborhood: A Literature Review. *International Journal of Sustainable Land Use and Urban Planning.* 2013;1(1):42-63.

173. Heath GW, Brownson RC, Kruger J, et al. The effectiveness of urban design and land use and transport policiies and practices to increase physical activity: A systematic review. *Journal of Physical Activity and Health.* 2006;3(Suppl 1):S55-S76.

174. Gebel K, Bauman AE, Petticrew M. The physical environment and physical activity: a critical appraisal of review articles. *Am J Prev Med.* 2007;32(5):361-369.

175. Bull F. Environmental Correlates of Physical Activity And Walking in Adults and Children: A Review of Reviews. In: Excellence NIoHaC, ed2007.

176. Giles-Corti B, Timperio A, Bull F, Pikora T. Understanding physical activity environmental correlates: increased specificity for ecological models. *Exerc Sport Sci Rev.* 2005;33(4):175-181.

177. Rodriguez DA, Brown AL, Troped PJ. Portable global positioning units to complement accelerometry-based physical activity monitors. *Med Sci Sports Exerc.* 2005;37(11 Suppl):S572-581.

178. Handy SL, Cao X, Mokhtarian PL. The causal influence of neighborhood design on physical activity within the neighborhood: evidence from Northern California. *Am J Health Promot.* 2008;22(5):350-358.

179. Troped PJ, Wilson JS, Matthews CE, Cromley EK, Melly SJ. The built environment and location-based physical activity. *Am J Prev Med.* 2010;38(4):429-438.

180. Baar J, Romppel M, Igel U, Brahler E, Grande G. The independent relations of both residential self-selection and the environment to physical activity. *Int J Environ Health Res.* 2015;25(3):288-298.

181. Van Dyck D, Cardon G, Deforche B, Owen N, De Bourdeaudhuij I. Relationships between neighborhood walkability and adults' physical activity: How important is residential self-selection? *Health Place.* 2011;17(4):1011-1014.

182. Owen N, Cerin E, Leslie E, et al. Neighborhood walkability and the walking behavior of Australian adults. *Am J Prev Med.* 2007;33(5):387-395.

183. Cao X, Handy SL, Mokhtarian PL. The influences of the built environment and residential self-selection on pedestrian behavior: evidence from Austin, TX. *Transportation* 2006;33:1-20.

184. Boone-Heinonen J, Guilkey DK, Evenson KR, Gordon-Larsen P. Residential self-selection bias in the estimation of built environment effects on physical activity between adolescence and young adulthood. *Int J Behav Nutr Phys Act.* 2010;7:70.

185. Sallis JF, De Bourdeaudhuij I, Owen N. International Physical Activity and the Environment Network. 2012; http://www.ipenproject.org.

186. Kerr J, Emond JA, Badland H, et al. Perceived Neighborhood Environmental Attributes Associated with Walking and Cycling for Transport among Adult Residents of 17 Cities in 12 Countries: The IPEN Study. *Environ Health Perspect.* 2015.

187. Gardner MJ, Altman DG. Confidence intervals rather than P values: estimation rather than hypothesis testing. *Br Med J (Clin Res Ed).* 1986;292(6522):746-750.

188. du Prel JB, Hommel G, Rohrig B, Blettner M. Confidence interval or p-value?: part 4 of a series on evaluation of scientific publications. *Dtsch Arztebl Int.* 2009;106(19):335-339.

189. Bland M, Peacock J. Interpreting statistics with confidence. *The Obstetrician and Gynaecologist.* 2002;4:176-180.

190. Dygryn J, Mitas J, Stelzer J. The influence of built environment on walkability using geographic information system. *Journal of Human Kinetics.* 2010;24:93-99.

191. Robertson LB, Ward Thompson C, Aspinall P, Millington C, McAdam C, Mutrie N. The influence of the local neighbourhood environment on walking levels during the Walking for Wellbeing in the West pedometer-based community intervention. *J Environ Public Health.* 2012;2012:974786.

192. Van Holle V, Van Cauwenberg J, Van Dyck D, Deforche B, Van de Weghe N, De Bourdeaudhuij I. Relationship between neighborhood walkability and older adults' physical activity: results from the Belgian Environmental Physical Activity Study in Seniors (BEPAS Seniors). *Int J Behav Nutr Phys Act.* 2014;11:110.

193. Van Cauwenberg J, De Bourdeaudhuij I, De Meester F, et al. Relationship between the physical environment and physical activity in older adults: a systematic review. *Health Place.* 2011;17(2):458-469.

194. Eriksson U, Arvidsson D, Gebel K, Ohlsson H, Sundquist K. Walkability parameters, active transportation and objective physical activity: moderating and mediating effects of motor vehicle ownership in a cross-sectional study. *Int J Behav Nutr Phys Act.* 2012;9:123.

195. Friederichs SA, Kremers SP, Lechner L, de Vries NK. Neighborhood walkability and walking behavior: the moderating role of action orientation. *J Phys Act Health.* 2013;10(4):515-522.

196. Steinmetz-Wood M, Kestens Y. Does the effect of walkable built environments vary by neighborhood socioeconomic status? *Prev Med.* 2015;81:262-267.

197. Van Dyck D, Cardon G, Deforche B, Sallis JF, Owen N, De Bourdeaudhuij I. Neighborhood SES and walkability are related to physical activity behavior in Belgian adults. *Prev Med.* 2010;50 Suppl 1:S74-79.

198. McCormack GR, Shiell A. In search of causality: a systematic review of the relationship between the built environment and physical activity among adults. *Int J Behav Nutr Phys Act.* 2011;8:125.

199. Cohen DA, Golinelli D, Williamson S, Sehgal A, Marsh T, McKenzie TL. Effects of park improvements on park use and physical activity: policy and programming implications. *Am J Prev Med.* 2009;37(6):475-480.

200. Evenson KR, Herring AH, Huston SL. Evaluating change in physical activity with the building of a multi-use trail. *Am J Prev Med.* 2005;28(2 Suppl 2):177-185.

201. Wells NM, Yang Y. Neighborhood design and walking. A quasi-experimental longitudinal study. *Am J Prev Med.* 2008;34(4):313-319.

202. Durand CP, Andalib M, Dunton GF, Wolch J, Pentz MA. A systematic review of built environment factors related to physical activity and obesity risk: implications for smart growth urban planning. *Obes Rev.* 2011;12(5):e173-182.

203. Ferdinand AO, Sen B, Rahurkar S, Engler S, Menachemi N. The relationship between built environments and physical activity: a systematic review. *Am J Public Health.* 2012;102(10):e7-e13.

204. Van Holle V, Deforche B, Van Cauwenberg J, et al. Relationship between the physical environment and different domains of physical activity in European adults: a systematic review. *BMC Public Health.* 2012;12:807.

205. Grasser G, Van Dyck D, Titze S, Stronegger W. Objectively measured walkability and active transport and weight-related outcomes in adults: a systematic review. *Int J Public Health.* 2013;58(4):615-625.

206. Moran M, Van Cauwenberg J, Hercky-Linnewiel R, Cerin E, Deforche B, Plaut P. Understanding the relationships between the physical environment and physical activity in older adults: a systematic review of qualitative studies. *Int J Behav Nutr Phys Act.* 2014;11:79.

207. Jack E, McCormack GR. The associations between objectively-determined and self-reported urban form characteristics and neighborhood-based walking in adults. *Int J Behav Nutr Phys Act.* 2014;11:71.

208. Hurvitz PM, Moudon AV, Kang B, Saelens BE, Duncan GE. Emerging technologies for assessing physical activity behaviors in space and time. *Front Public Health.* 2014;2:2.

209. Troped PJ, Wilson JS, Matthews CE, Cromley EK, Melly SJ. The built environment and location-based physical activity. *American journal of preventive medicine.* 2010;38(4):429-438.

210. Rodriguez DA, Brown AL, Troped PJ. Portable global positioning units to complement accelerometry-based physical activity monitors. *Medicine and science in sports and exercise.* 2005;37(11 Suppl):S572-581.

211. Brondeel R, Pannier B, Chaix B. Using GPS, GIS, and Accelerometer Data to Predict Transportation Modes. *Med Sci Sports Exerc.* 2015.

212. Chaix B, Kestens Y, Duncan S, et al. Active transportation and public transportation use to achieve physical activity recommendations? A combined GPS, accelerometer, and mobility survey study. *Int J Behav Nutr Phys Act.* 2014;11:124.

213. Dunton GF, Almanza E, Jerrett M, Wolch J, Pentz MA. Neighborhood park use by children: use of accelerometry and global positioning systems. *Am J Prev Med.* 2014;46(2):136-142.

214. Burgoine T, Jones AP, Namenek Brouwer RJ, Benjamin Neelon SE. Associations between BMI and home, school and route environmental exposures estimated using GPS and GIS: do we see evidence of selective daily mobility bias in children? *Int J Health Geogr.* 2015;14:8.

215. Gilmour H. Physically active Canadians. *Health Rep.* 2007;18(3):45-65.

216. Tudor-Locke C, Bittman M, Merom D, Bauman A. Patterns of walking for transport and exercise: a novel application of time use data. *Int J Behav Nutr Phys Act.* 2005;2:5.

217. Mier N, Medina AA, Ory MG. Mexican Americans with type 2 diabetes: perspectives on definitions, motivators, and programs of physical activity. *Prev Chronic Dis.* 2007;4(2):A24.

218. Frank LD, Kershaw SE, Chapman JE, Campbell M, Swinkels HM. The unmet demand for walkability: Disparities between preferences and actual choices for residential environments in Toronto and Vancouver. *Can J Public Health.* 2015;106(1 Suppl 1):eS12-21.

219. Dasgupta K, Joseph L, Pilote L, Strachan I, Sigal RJ, Chan C. Daily steps are low year-round and dip lower in fall/winter: findings from a longitudinal diabetes cohort. *Cardiovasc Diabetol.* 2010;9:81.

220. Tudor-Locke C, Bassett DR, Jr. How many steps/day are enough? Preliminary pedometer indices for public health. *Sports medicine.* 2004;34(1):1-8.

221. Camhi SM, Sisson SB, Johnson WD, Katzmarzyk PT, Tudor-Locke C. Accelerometer-determined moderate intensity lifestyle activity and cardiometabolic health. *Prev Med.* 2011;52(5):358-360.

222. Colley RC, Garriguet D, Janssen I, Craig CL, Clarke J, Tremblay MS. Physical activity of Canadian adults: accelerometer results from the 2007 to 2009 Canadian Health Measures Survey. *Health Rep.* 2011;22(1):7-14.

223. Bürgmann R, Hiller G, Ferretti A, Novali F. Resolving vertical tectonics in the San Francisco Bay Area from permanent scatterer InSAR and GPS analysis. *Geology.* 2006;34 (3):221-224.

224. Gili JA, Corominas J, Rius J. Using Global Positioning System techniques in landslide monitoring. . *Eng Geol.* 2000;55:167-192.

225. Schlecht EC, Hulsebusch C, Mahler F, Becker K. The use of differentially corrected global positioning system to monitor activities of cattle at pasture. *Applied Animal Behaviour Science.* 2004;85:185-202.

226. Schutz Y, Herren R. Assessment of speed of human locomotion using a differential satellite global positioning system. *Medicine and science in sports and exercise.* 2000;32(3):642-646.

227. Oliver M, Badland H, Mavoa S, Duncan MJ, Duncan S. Combining GPS, GIS, and accelerometry: methodological issues in the assessment of location and intensity of travel behaviors. *J Phys Act Health.* 2010;7(1):102-108.

228. Quigg R, Gray A, Reeder AI, Holt A, Waters DL. Using accelerometers and GPS units to identify the proportion of daily physical activity located in parks with playgrounds in New Zealand children. *Preventive medicine.* 2010;50(5-6):235-240.

229. Rosenberg DE, Bombardier CH, Hoffman JM, Belza B. Physical activity among persons aging with mobility disabilities: shaping a research agenda. *Journal of aging research.* 2011;2011:708510.

230. Tudor-Locke C, Ainsworth BE, Thompson RW, Matthews CE. Comparison of pedometer and accelerometer measures of free-living physical activity. *Medicine and science in sports and exercise.* 2002;34(12):2045-2051.

231. Freedson PS, Miller K. Objective monitoring of physical activity using motion sensors and heart rate. *Research quarterly for exercise and sport.* 2000;71(2 Suppl):S21-29.

232. Qasem L, Cardew A, Wilson A, et al. Tri-axial dynamic acceleration as a proxy for animal energy expenditure; should we be summing values or calculating the vector? *PLoS One.* 2012;7(2):e31187.

233. Hiilloskorpi HK, Pasanen ME, Fogelholm MG, Laukkanen RM, Manttari AT. Use of heart rate to predict energy expenditure from low to high activity levels. *Int J Sports Med.* 2003;24(5):332-336.

234. Levy AR, Bensimon DR, Mayo NE, Leighton HG. Inclement weather and the risk of hip fracture. *Epidemiology.* 1998;9(2):172-177.

235. Liberal Party of Canada. Public Transit. 2015; https://www.liberal.ca/realchange/public-transit%E2%80%A8/.

236. Promenade Fleuve-Montagne. 2016; http://ville.montreal.qc.ca/portal/page?_pageid=7377,142290879&_dad=portal&_schema=PORTAL. Accessed March 15, 2016.

237. Rose G. Sick individuals and sick populations. *Int J Epidemiol.* 2001;30(3):427-432; discussion 433-424.

238. Active Living Resaerch: Promoting active-friendly communities. 2015; http://activelivingresearch.org. Accessed September 1, 2015.

239. De Bourdeaudhuij I. Belgian Environmental Physical Activity Study 2007-2008; http://www.ipenproject.org/Belgium.html. Accessed September 1, 2015.

240. Centre for Built Environment and Health http://www.see.uwa.edu.au/research/cbeh. Accessed September 1, 2015.

241. Study of Environmental and Individual Determinants (SEID I & II). http://www.see.uwa.edu.au/research/cbeh/projects/seid. Accessed September 1, 2015.

242. RESIDential Environment Study (RESIDE). http://www.see.uwa.edu.au/research/cbeh/projects/reside. Accessed September 1, 2015.

243. Sallis JF, De Bourdeaudhuij I, Owen N. International Physical Activity and the Environment Network. http://www.ipenproject.org. Accessed September 1, 2015.

244. Sallis JF, Saelens BE, Frank LD, et al. Neighborhood built environment and income: examining multiple health outcomes. *Soc Sci Med.* 2009;68(7):1285-1293.

245. Nykiforuk C. Policy, Location and Access in Community Environments (PLACE) Research Lab. 2015; https://uofa.ualberta.ca/public-health/about/faculty-staff/academic-listing/candace-nykiforuk.

246. Chaix B. RECORD: A study of territorial disparities in health. 2015; http://www.record-study.org/r_home/index.html. Accessed October 5, 2015, 2015.

247. Spence JC. Sedentary Living Laboratory. 2015; http://www.ualberta.ca/~sedlab/Sedlivlab.htm. Accessed October 5, 2015.

248. Sundquist K, Eriksson U, Kawakami N, Skog L, Ohlsson H, Arvidsson D. Neighborhood walkability, physical activity, and walking behavior: the Swedish Neighborhood and Physical Activity (SNAP) study. *Soc Sci Med.* 2011;72(8):1266-1273.

249. Reis RS. International Physical Activity and the Environment Network: Project SPACEs of Curitiba - Understanding the physical activity practices in the community. 2012; http://www.ipenproject.org/Brazil.html. Accessed October 5, 2015, 2015.

250. Kestens Y. SPHERE Lab. 2015; http://www.spherelab.org. Accessed October 5, 2015, 2015.

251. Forsyth A, Schmitz K, Oakes M. Twin Cities Walking Study. http://designforhealth.net/resources/other/twin-cities-walking-study/. Accessed October 5, 2015.

APPENDIX A | Major research initiatives occurring worldwide

Overview of the major research initiatives that are underway in order to increase our understanding of the role of neighbourhood environments on human health.

Research Initiative	Reference	Principal Investigators	Location
Active Living Research Group	238	James Sallis; Lawrence Frank; Jacqueline Kerr	USA
Belgian Environmental Physical Activity Study (BEPAS)	239	Ilse De Bourdeaudhuij; Delfian Van Dyck	Ghent, Belgium
Centre for Built Environment and Health Study of Environmental and Individual Determinants (SEID I & II) Residential Environment (RESIDE) Study	240-242	Fiona Bull; Billie Giles-Corti; Konrad Jamrozik; Rob Donovan	Australia
International Physical Activity and the Environment Network (IPEN)	243	James Sallis; Ilse De Bourdeaudhuij; Neville Owen	International*
Neighbourhood Quality of Life Studies (NQLS)	244	James Sallis; Lawrence Frank; Brian Saelens	USA
Physical Activity in Localities and Community Environments (PLACE)	182	Neville Owen	Australia
Policy, Location, and Access in Community Environments (PLACE)	245	Candice Nykiforuk	Edmonton, Alberta
Residential Environment and Coronary heart Disease (RECORD) Cohort Study	246	Basile Chaix	Paris, France
Sedentary Living Laboratory	247	John Spence	Edmonton, Alberta
Swedish Neighborhood and Physical Activity (SNAP) Study	248	Kristina Sundquist; David Arvidsson; Henrik Ohlsson	Stockholm, Sweden
Project SPACEs of Curitiba - Understanding the physical activity practices in the community	249	Rodrigo Siqueira Reis	Curitiba, Brazil
Spatial Health Research (SPHERE) Lab	250	Yan Kestens	Montréal, QC
Twin Cities Walking Study	251	Anne Forsyth; Kathryn Schmitz; Michael Oakes	Minnesota, USA

* There are many studies being conducted worldwide as part of the IPEN initiative. Only selected IPEN studies are listed above (i.e., BEPAS, NQLS, PLACE, SNAP, SPACEs). Other similar studies are being conducted in Colombia, the Czech Republic, Denmark, Hong Kong, Mexico, New Zealand, Spain, and the United Kingdom

International Journal of Epidemiology, 2015, 1–6
doi: 10.1093/ije/dyv164
Diversion

Diversion

Substantiating the impact of John Snow's contributions using data deleted during the 1936 reprinting of his original essay *On the Mode of Communication of Cholera*

Text

Samantha Hajna,* David L Buckeridge and James A Hanley

Department of Epidemiology, Biostatistics and Occupational Health, McGill University, Montréal, QC, Canada

*Corresponding author. Department of Epidemiology, Biostatistics and Occupational Health, McGill University, 1020 Pine Avenue West, Montréal, QC, H3A 1A2, Canada. E-mail: samantha.hajna@mail.mcgill.ca

Accepted 31 July 2015

Introduction

John Snow is considered a founder of modern epidemiology and his contributions to the field are highlighted in many introductory courses in medicine.[1] Whereas all epidemiologists are familiar with the account of the Broad Street pump,[2] fewer are familiar with the much larger and more compelling Grand Experiment that Snow exploited in South London.[3–5] In his well-known essay *On the Mode of Communication of Cholera*,[6] Snow devoted 25 pages to listing the details surrounding the deaths of 334 people who died during the first 4 weeks of the 1854 epidemic. John Snow, along with his assistant Mr John Joseph Whiting, visited the dwellings of every person who died from cholera in South London during this period. With utmost attention to detail and at great risk to their own personal health, Snow and Whiting recorded important details surrounding the deaths of these individuals. These data provided undeniable evidence that cholera was spread through the ingestion of contaminated water and, as noted by Sir Austin Bradford Hill, are one of the reasons why England and the rest of the developed world have been free from epidemic cholera since the late 1800s.[7]

In 1855, John Snow printed 300 copies of his original essay *On the Mode of Communication of Cholera* at a personal cost of more than £200.[6] He sold only 56 copies.[7] In 1936 Wade Hampton Frost, a professor of epidemiology at the Johns Hopkins School of Hygiene and Public Health, reprinted Snow's original essay; but he deleted the South London data that Snow collected at such a great personal cost and that were of such great epidemiological value.[8] Frost only listed the first 23 of the 334 entries that John Snow recorded in his original essay, and followed this truncated list with the words: 'In the original publication the list of deaths is continued in this form for a total of twenty-five pages (p. 139)'.[8] In contrast to the small number of copies that John Snow sold, thousands of copies of the1936 reprint were published and widely disseminated. Unfortunately the wide availability of this reprint has perpetuated the omission of these data and undermines the role that they played in identifying the mode of communication of cholera.

To commemorate the 160th anniversary of the publication of Snow's second edition of *On the Mode of Communication of Cholera*[6] and to redress this epidemiological slight, we highlight John Snow's important work in South London, unearth the original data that Snow collected at great risk to his own personal health and present a first-time mapping of these data in time and space. We trust that this piece will foster a deeper appreciation for John Snow's contribution to epidemiology and increase respect for small yet valuable epidemiological data.

The Grand Experiment

In 1854 two water companies, the Southwark and Vauxhall Waterworks Company and the Lambeth Waterworks Company, supplied water to South London. The intake of Southwark and Vauxhall was located next to Battersea Park. Because of its close proximity to downtown, the intake drew water contaminated with sewage that had emptied into the River Thames.[6] In his book *Microscopic Examination of the Water Supplied to the Inhabitants of London and the Suburban Districts,* Arthur Hill Hassall, a British physician, stated that 'This water was the most disgusting which I have ever examined: when I first saw the water of the Southwark Company, I thought it as bad as it could be, but this far exceeded it in the peculiarly repulsive character of living contents'.[9] The intake of the Lambeth Company was upstream of central London at Thames Ditton, and thus provided a much cleaner water source.[6]

To exploit the Grand Experiment, Snow and his assistant, Mr John Joseph Whiting, visited the addresses where each of the cholera deaths occurred and recorded the details surrounding each death. Snow placed Mr Whiting in charge of visiting the addresses that lay in districts where water was supplied only by the Southwark and Vauxhall Waterworks Company. Mr Whiting's task was to make an enquiry at each house to determine if the water was indeed supplied by the Southwark and Vauxhall Waterworks Company or if the residents drew their water from another source, such as the ditch, drain or river.

John Snow took the more difficult task of visiting the districts in South London that were supplied by both the Southwark and Vauxhall Waterworks Company and the Lambeth Waterworks Company. Snow asked residents at each address to identify their water supplier. If unknown, Snow asked them to look at their water payment receipts. If the water company still could not be identified, Snow employed a chemical test by which he was able to identify the company based on the salt content of the water.

> The test I employed was founded on the great difference in the quantity of chloride of sodium contained in the two kinds of water at the time I made the inquiry. On adding solution of nitrite of silver to a gallon of the water of the Lambeth Company, obtained at Thames Ditton, beyond the reach of the sewage of London, only 2.28 grains of chloride of silver were obtained, indicating the presence of 0.95 grains of chloride of sodium in the water. On treating the water of the Southwark and Vauxhall Company in the same manner, 91 grains of chloride of silver were obtained, showing the presence of 37.9 grains of common salt per gallon. Indeed, the difference in appearance on adding nitrate of silver to the two kinds of water was so great, that they could be at once distinguished without any further trouble (p. 78).[6]

To verify that the information provided by the residents and the results of his chemical tests were correct, Snow ascertained that the time that the main supplies were turned on by the water companies corresponded to the time that the water appeared in the home.[6]

Based on listings provided by the Registrar General's Office, Snow and Whiting visited the homes of 334 people who had died of cholera between 8 July and 5 August 1854. Of these, 286 received their water from the Southwark and Vauxhall Waterworks Company and 14 received their water from the Lambeth Waterworks Company. The remaining 34 received water from other sources (e.g. directly from the River Thames, from pumps or from ditches). Based on this and the reported number of houses that the companies supplied water to (Southwark and Vauxhall Waterworks Company: 40 046; Lambeth Waterworks Company: 26 107), Snow estimated that the incidence of fatal cholera was 14 times higher in households supplied by the Southwark and Vauxhall Waterworks Company.[6] (Note: The incidence of fatal cholera is 13.3 times higher in household supplied by the Southwark and Vauxhall Waterworks Company. When John Snow calculated the incidence he calculated the proportion of deaths for every 10 000 households and rounded the numerators and denominators to the nearest 10 before dividing (i.e., 71/5), giving him an incidence ratio of 14.)

The majority of districts in which the 334 deaths occurred were supplied with water from both the Southwark and Vauxhall Waterworks Company and the Lambeth Waterworks Company. This provided near perfect randomization of people to one or the other water source and added weight to John Snow's theory that cholera was transmitted through the ingestion of contaminated water. According to Snow:

> The mixing of the supply is of the most intimate kind . . . each Company supplies both rich and poor, both large houses and small; there is no difference either in the condition or occupation of the persons receiving the water of the different Companies (pp. 74–75) . . . [and this intermixing provided] . . . incontrovertible proof on one side or the other (p. 74) [for the mode of communication of cholera].[6]

John Snow's investigation into the mode of communication of cholera did not come without criticism.[1,10–12] One notable critic of Snow's work was Edmund Alexander Parkes, a proponent of the miasma theory.[10] In 1855 Parkes published a critical review of Snow's major essay published earlier in the same year.[13] Although Parkes underestimated the strength of Snow's evidence,[10] he was not amiss in pointing out that Snow's work was not perfect. John Snow's work in South London had one important limitation.[7] Snow did not know how many homes the two water companies supplied water to in the districts that were served by both water companies. As a result, he was only able to compare the absolute number of deaths that occurred among customers supplied by the two water companies, not the rates of death.[7] Snow recognized this as a limitation, stating in an article that he published shortly after his enquiry in South London that:

> I hope shortly to learn the number of houses in each sub-district supplied by each of the Water Companies respectively, when the effect of the impure water in propagating cholera will be shown in a very striking manner, and with great detail (p. 365).[14]

Shortly thereafter, the General Board of Health released statistics relating to the number of households that were supplied by both of the water companies in each district and sub-district. In October of 1856 Snow published a paper in which he demonstrated that in the sub-districts supplied by both water companies, the death rate from cholera was the highest among people supplied by the Southwark and Vauxhall Water Company.[7,15] Snow's work using both absolute numbers and rates provided compelling evidence in support of his theory that cholera was spread largely through the ingestion of contaminated water. Sir Bradford Hill acknowledged the value of Snow's analyses using both absolute numbers and rates, stating 'Snow must have bitterly regretted that he could not do it in his major work. However that may be, the contrast, whether in absolute numbers of deaths or in total districts, was so great as not to be mistaken (p. 50)'.[7]

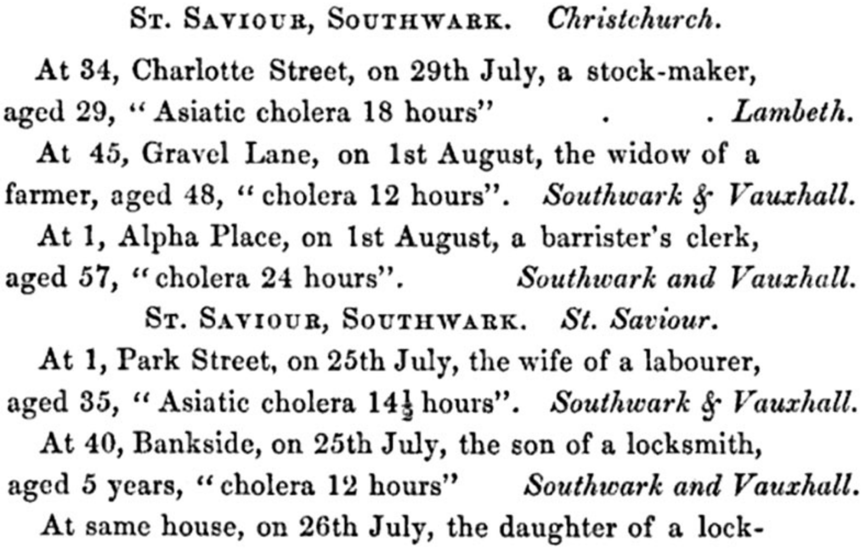
Mapping the South London deaths

In an appendix to the second edition of his 1855 essay, John Snow provided a detailed record of the 334 deaths from cholera that occurred in South London between 8 July and 5 August 1854. According to Snow, this information was included in the second edition of his essay 'as a guarantee that the water supply was inquired into, and to afford any person who wishes it an opportunity of verifying the results (p. 80)'.[6] The information that John Snow recorded included the address at which each cholera-related death occurred, the date of death, the occupation and the age of the deceased, the duration of symptoms before death and the water source (Figure 1).

We mapped the locations of the cholera deaths that occurred in South London on Reynolds' Shilling Coloured Map of London,[16] using the Create Features/Point Construction Tool in ArcMap 10.1 (ESRI; Redlands, CA). The location of each address was identified using Reynolds' Index of streets,[16] Lockie's Topography of London,[17] Large's Way about London[18] or the Map of London 1868 by Edward Weller.[19] Unless the precise location of the address was visualized, the addresses were mapped in the centre of the street segment. The cholera deaths were animated by time using the Animation Manager (ArcMap 10.1).

Findings

We identified the locations of 286 of the 334 cholera deaths that occurred between 8 July and 5 August 1854 in South London (85.6%). Of these, 14 were supplied by the Lambeth Waterworks Company and 272 were supplied by the Southwark and Vauxhall Waterworks Company. The locations of the cholera deaths were mapped (Figure 2)



ST. SAVIOUR, SOUTHWARK. *Christchurch.*

At 34, Charlotte Street, on 29th July, a stock-maker, aged 29, "Asiatic cholera 18 hours" . . *Lambeth.*

At 45, Gravel Lane, on 1st August, the widow of a farmer, aged 48, "cholera 12 hours". *Southwark & Vauxhall.*

At 1, Alpha Place, on 1st August, a barrister's clerk, aged 57, "cholera 24 hours". *Southwark and Vauxhall.*

ST. SAVIOUR, SOUTHWARK. *St. Saviour.*

At 1, Park Street, on 25th July, the wife of a labourer, aged 35, "Asiatic cholera 14½ hours". *Southwark & Vauxhall.*

At 40, Bankside, on 25th July, the son of a locksmith, aged 5 years, "cholera 12 hours" *Southwark and Vauxhall.*

At same house, on 26th July, the daughter of a lock-

Figure 1. Excerpt of the information that John Snow recorded in the appendix of the second edition of his essay *On the Mode of Communication of Cholera* (1855) for each cholera death that occurred in South London between 8 July and 5 August 1854.

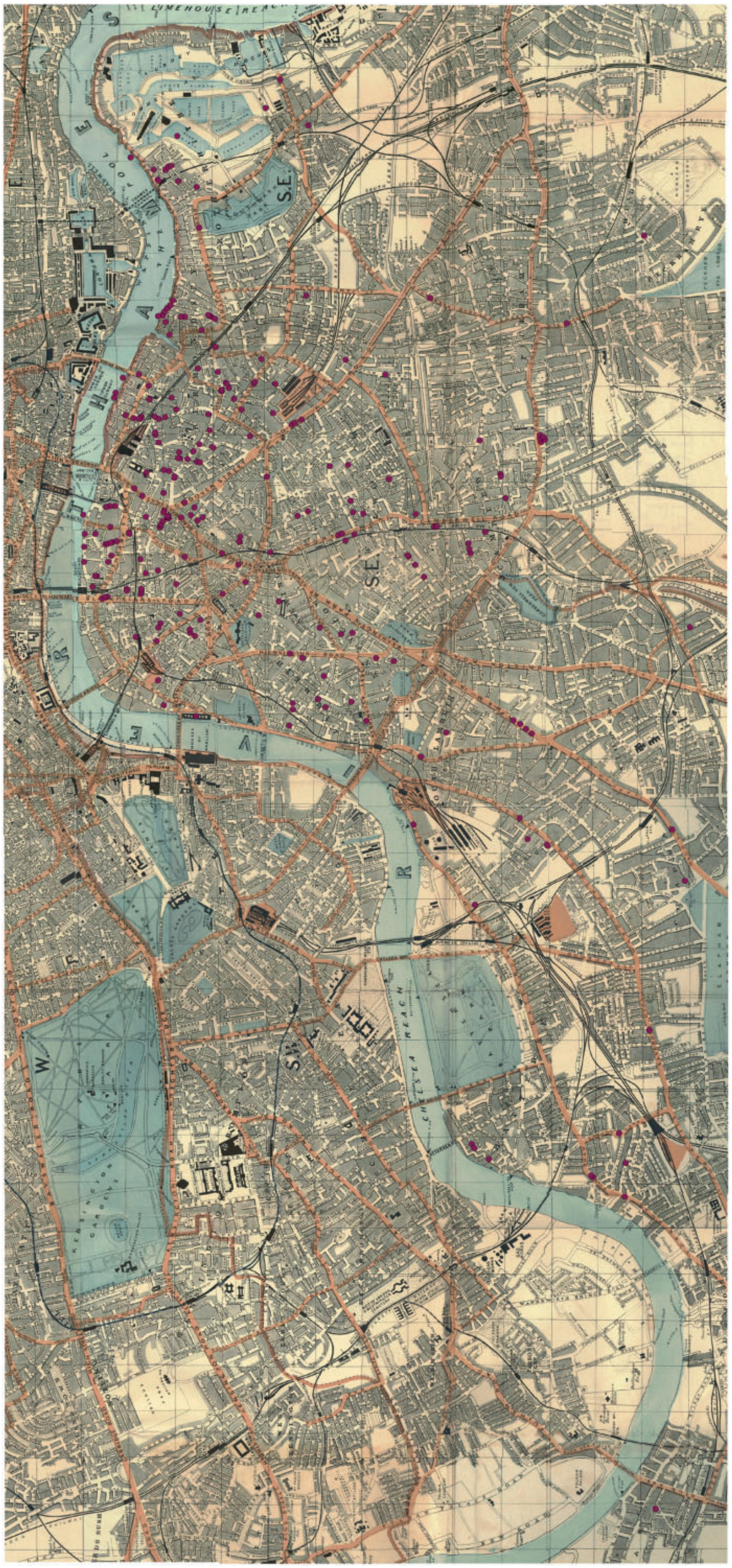


Figure 2. Locations of the cholera deaths occurring in South London between 8 July and 5 August 1854.

and animated by the date of death (Supplementary Video 1). We encourage researchers interested in completing the mapping of the South London outbreak to identify the locations of the 48 addresses that we were unable to find (Supplementary File 1, available as Supplementary data at *IJE* online).

No temporal trend in cholera deaths was observed. This was expected, given that cholera was spread largely by the water supplied by the Southwark and Vauxhall Company and less from person-to-person contact. Most of the cholera deaths that occurred between 8 July and 5 August clustered around the northern part of South London. This was also expected as this was the area with the highest population density.

Discussion

Since Snow published his well-known essay *On the Mode of Communication of Cholera*, 160 years have passed. Sir Austin Bradford Hill, in his piece commemorating the 100-year anniversary of the publication of this essay, acknowledged the impact of John Snow's work, stating:

> For close upon 100 years we have been free in this country from epidemiologic cholera, and it is a freedom which, basically, we owe to the logical thinking, acute observations and simple sums of Dr. John Snow (p. 50).[7]

Since then many others have also highlighted John Snow's contribution to the field of epidemiology.[11,20–24]

What makes Snow's work surrounding the Grand Experiment extraordinary was his attention to detail, the painstaking effort that he expended and the personal risk that he took upon himself to collect these data. From visiting each residence where a cholera death occurred, to conducting chemical tests to determine the water source, to investigating water bills, to ascertaining the time at which the water supplies were turned on, to describing the need to balance comparator groups, John Snow provided incontrovertible evidence that cholera was spread largely through the ingestion of contaminated water. Unfortunately these data, that he so painstakingly collected at great personal risk, were unceremoniously deleted from the 1936 reprinting of his essay. To commemorate the 160th anniversary of the publication of John Snow's second edition of *On the Mode of Communication of Cholera*,[6] we have presented a first-time mapping in space and time of these data. Albeit small, these data demonstrate the value of well-conducted shoe-leather epidemiology and should be credited alongside the rest of John Snow's work.

Supplementary Data

Supplementary data are available at *IJE* online.

Funding

SH was supported by a Canadian Institutes of Health Research Doctoral Research Award.

Acknowledgements

We would like to thank Rolina Van Gaalen for parsing the data that John Snow recorded in the second edition of his essay *On the Mode of Communication of Cholera* (1855) and Ruilan Shi for technical assistance with ArcGIS. SH conducted all of the spatial analyses and wrote the manuscript. JH conceived the idea and edited the manuscript for content. DB edited the manuscript for content.

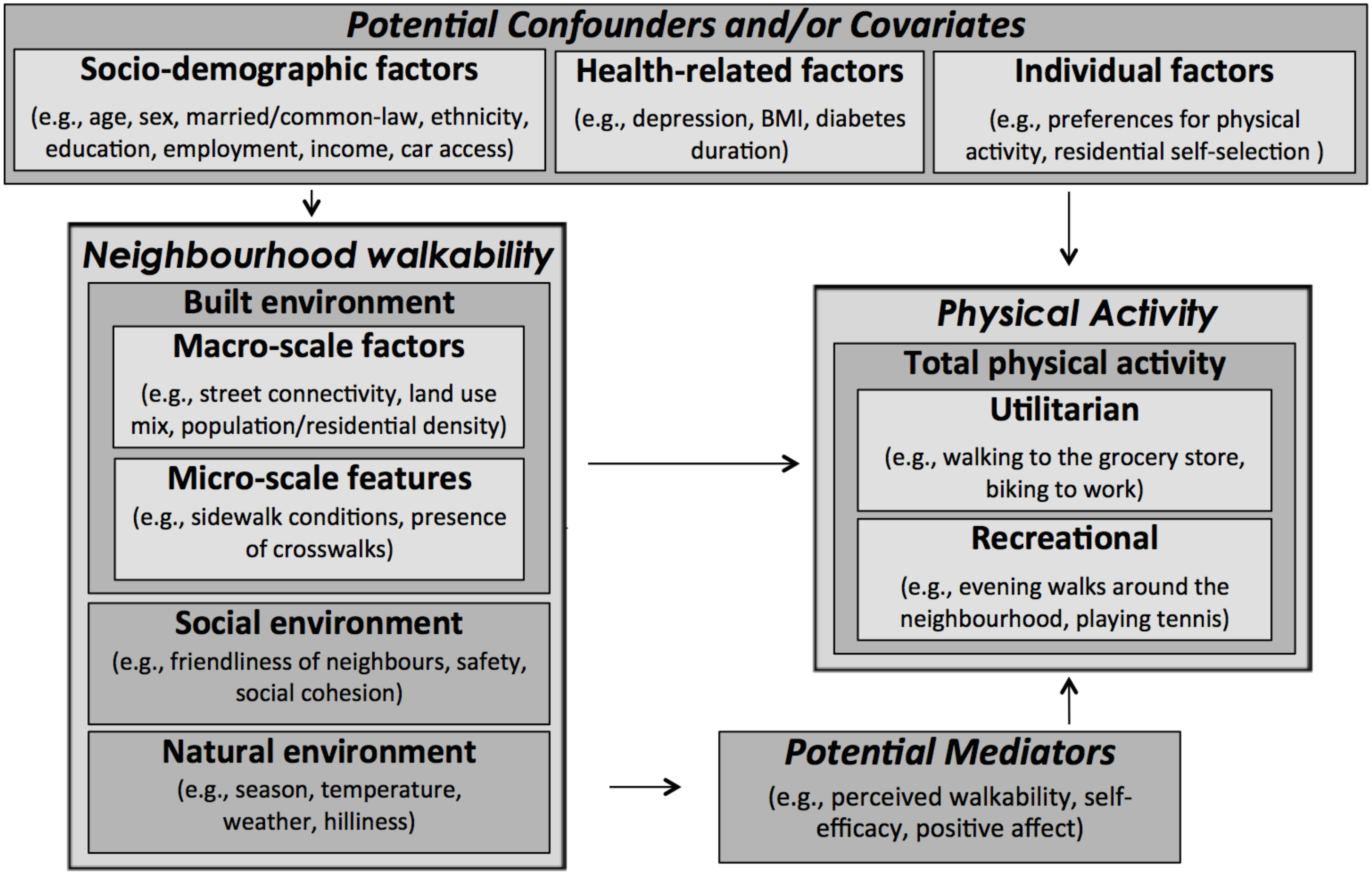
Conflict of interest: There is no conflict of interest to disclose.

References

1. Davey Smith G. Commentary: Behind the Broad Street pump: aetiology, epidemiology and prevention of cholera in mid-19th century Britain. *Int J Epidemiol* 2002;**31**:920–32.
2. Buechner JS, Constantine H, Gjelsvik A. John Snow and the Broad Street pump: 150 years of epidemiology. *Med Health R I* 2004;**87**:314–15.
3. Bynum WF. In retrospect: On the mode of communication of cholera. *Nature* 2013;**495**:16970.
4. Froggatt SP. John Snow, Thomas Wakley, and The Lancet. *Anaesthesia* 2002;**57**:667–75.
5. Paneth N. Assessing the contributions of John Snow to epidemiology: 150 years after removal of the Broad Street pump handle. *Epidemiology* 2004;**15**:514–16.
6. Snow J. *On the Mode of Communication of Cholera*. London: John Churchill, 1855.
7. Hill AB. Snow; an appreciation. *Proc R Soc Med* 1955;**48**: 1008–12.
8. Snow J, Frost WH, Richardson BW. *Snow on cholera: Being a reprint of two papers*. New York, NY: Commonwealth Fund, 1936.
9. Hassall AH. *Microscopic Examination of the Water Supplied to the Inhabitants of London and the Suburban Districts*. London: Samuel Highley, 1850.
10. Bergman BP. Commentary: Edmund Alexander Parkes, John Snow and the miasma controversy. *Int J Epidemiol* 2013;**42**:1562–65.
11. Lilienfeld DE. Commentary: John Snow's 'On the supposed influence of offensive trades on mortality': the 'Snow paradigm'. *Int J Epidemiol* 2013;**42**:1240–41.
12. Vandenbroucke JP. Commentary: Snow's paper on 'offensive trades'—with the benefit of 150 years of hindsight. *Int J Epidemiol* 2013;**42**:1235–38.
13. Parkes EA. Mode of communication of cholera by John Snow, MD: second edition—London, 1855, pp. 162. *Int J Epidemiol* 2013;**42**:1543–52.
14. Snow J. *On the Communication of Cholera by Impure Thames Water*. London: John Churchill, 1854.

15. Snow J. Cholera and the water supply in the south districts of London in 1854. *Jour Pub Health and Sanitary Rev* 1856;**2:** 239–57.
16. Reynolds J. *Cartographer Reynolds' Shilling Coloured Map of London with Illustrated Visitors Guide, Street Directory, Omnibus and Tramcar Routes, Clue Map etc*. London: James Reynold, 1859.
17. Lockie J. *Lockie's Topography of London*. London: S. Couchman, 1810.
18. Large H. *Large's Way about London*. London: Offices of 'Large's Way about London', 1867.
19. Weller E, Dower J. *Map of London 1868*. London: G. W. Bacon, 1868.
20. Vandenbroucke JP. Changing images of John Snow in the history of epidemiology. *Soz Praventivmed* 2001;**46:**288–93.
21. Snow SJ. John Snow: the making of a hero? *Lancet* 2008;**372:**22–23.
22. Smith CE. The Broad Street pump revisited. *Int J Epidemiol* 1982;**11:**99–100.
23. Cameron D, Jones IG. John Snow, the Broad Street pump and modern epidemiology. *Int J Epidemiol* 1983;**12:**393–96.
24. Morens DM. Commentary: cholera conundrums and proto-epidemiologic puzzles. The confusing epidemic world of John Lea and John Snow. *Int J Epidemiol* 2013;**42:**43–52.

APPENDIX C | Summary of the potential confounders/covariates of the neighbourhood walkability-physical activity relationship



Neighborhood Walkability

Field Validation of Geographic Information System Measures

Samantha Hajna, MSc, Kaberi Dasgupta, MD, MSc, FRCPC, Max Halparin, BA, Nancy A. Ross, PhD

Appendix A

Overview of the items that were assessed as part of the neighborhood audits

Item	Response options
Number of land uses	1, 2, >2
Slope steepness	Steep hill, slight hill, flat
Sidewalk presence	None, one side, both sides
Sidewalk condition	Poor, fair, good
Buffers between road and sidewalk	No buffer, parked cars, trees or other
Sidewalk width	<4 feet, 4–8 feet, >8 feet
Number of lanes	>2, 2, 1
Medium- to high-volume driveways	>2, 1 or 2, 0
Traffic control devices	None, one side, both sides
Crossing aids	None, one side, both sides
Pedestrian lighting	None, one side, both sides
Roadway lighting	None, one side, both sides
Green space	None, private, public
Street amenities	None, few, many
Number of trees shading walking area	None or very few, some, many or dense
Overall cleanliness and maintenance	Poor, fair, good
Articulation in building designs	Little or none, some, highly articulated
Bus stops or metro	None, sign only, bench or shelter
Attractiveness	Poor, fair, good
Safety	Poor, fair, good
Utilitarian	Poor, fair, good

Appendix B

Overview of the items that were included in the calculation of the participant-reported neighborhood walkability

Item	Response options
Are there sidewalks in your neighborhood?	Yes, no
Condition of sidewalks	Very well maintained, somewhat maintained, not very well maintained
Condition of street lighting at night (in your neighborhood)	Very good, good, fair, poor, very poor
There is too much traffic to walk along the street where you live.	Strongly agree, somewhat agree, somewhat disagree, strongly disagree
There are stores within walking distance (in your neighborhood).	Strongly agree, somewhat agree, somewhat disagree, strongly disagree
It is easy to walk to a transit stop (in your neighborhood).	Strongly agree, somewhat agree, somewhat disagree, strongly disagree
There are many interesting sights while walking (in your neighborhood).	Strongly agree, somewhat agree, somewhat disagree, strongly disagree
Overall, people in my neighborhood are:	Very active, somewhat active, not very active, not at all active
How safe do you feel when walking in your neighborhood?	Extremely safe, quite safe, slightly safe, not at all safe

Appendix C

Eigenvalues and factor loadings from the principal component analysis of the participant-reported items that were assessed using the Neighborhood Walkability Survey

Question # and content		Factor 1: amenities (2.64)	Factor 2: neighborhood aesthetics and activity (1.33)	Factor 3: safety (1.30)
1	Are there sidewalks in your neighborhood?	0.88[a]	−0.01	−0.18
2	Condition of sidewalks	0.88[a]	−0.03	0.01
3	Condition of street lighting at night (in your neighborhood)	0.66[a]	−0.01	0.31
4	There is too much traffic to walk along the street where you live.	−0.11	−0.19	0.72
5	There are stores within walking distance (in your neighborhood).	0.60[a]	0.20	0.01
6	It is easy to walk to a transit stop (in your neighborhood).	0.43[a]	0.23	0.38
7	There are many interesting sights while walking (in your neighborhood).	0.08	0.77[a]	−0.04
8	Overall, people in my neighborhood are very active.	0.01	0.79[a]	0.03
9	How safe do you feel when walking in your neighborhood?	0.11	0.12	0.75[a]

Note: Eigenvalues are shown in parentheses following headings.

[a] Factor loadings ≥0.40

APPENDIX E │Supplemental material for *Manuscript 4*

File 1. Baseline characteristics of participants overall (n=3727), on whom complete covariate data were available (n=2949), and on whom complete covariate data were not available (n=778).

	Overall (n=3727)[a]	**Full data not available** (n=778)[b]	**Complete data** (n=2949)
	mean (SD)	mean (SD)	mean (SD)
Age, *years*	46.8 (17.0)	47.4 (19.2)	46.6 (16.4)
Body mass index, kg/m^2	27.3 (5.7)	27.3 (6.3)	27.3 (5.5)
Steps/day	7756 (3943)	6720 (4642)	7923 (3792)
Walk Score	48 (30)	54 (28)	46 (30)
	% (N)	% (N)	% (N)
Being a woman (*vs.* being a man)	53.2 (1981)	59.9 (466)	51.4 (1515)
Married/Common-law (*vs.* widowed, separated, divorced, or single/never married)	60.2 (2243)	41.8 (324)	65.1 (1919)
Have children ≤ 15 years old in household (yes *vs.* no)	34.2 (1274)	28.7 (223)	35.6 (1051)
Immigrant (yes *vs.* no)	22.2 (828)	31.0 (241)	19.9 (587)
Mood disorder (yes *vs.* no)	9.1 (338)	11.9 (92)	8.3 (246)
Good/very good/excellent perceived health (*vs.* fair/poor)	87.7 (3267)	77.9 (605)	90.3 (2662)
Total annual household income ≥$40000 (vs. <$40000)	77.5 (2490)	75.1 (199)	77.7 (2291)
Ever smoker (*vs.* never smoker)	51.1 (1900)	53.6 (412)	50.5 (1488)
Fall/winter assessment (*vs.* spring/summer assessment)	47.0 (1753)	41.7 (324)	48.5 (1429)
Rural location (*vs.* urban location)	13.0 (484)	7.7 (60)	14.4 (424)
≥ 1 hour/week of utilitarian walking (*vs.* < 1 hour/week)	63.6 (2371)	63.4 (493)	63.7 (1878)
≥ 6 hours/week of utilitarian walking (*vs.*< 6 hours/week)	18.4 (684)	20.3 (158)	17.8 (526)

[a] Body mass index (n=3692), steps/day (n=3424), married/common-law (n=3725), immigrant (n=3726), depressed (n=3723), total annual household income ≥$40000 (n=3214), ever smoker (n=3718), perceived health (n=3726), rural (n=3726).

[b] Body mass index (n=743), steps/day (n=475), married/common-law (n=776), immigrant (n=777), depressed (n=774), total annual household income ≥$40000 (n=265), ever smoker (n=769), perceived health (n=777), rural (n=777).

File 2. Mean changes in accelerometer-assessed steps/day, odds of ≥1 hour/week of utilitarian walking, and odds of ≥6 hours/week of utilitarian walking, across quartiles of GIS-derived walkability in fully-adjusted models using variable buffer shapes and sizes (n=2949).[a]

	Increment in Daily Steps (b, 95% CI)			
	Quartile 2	*Quartile 3*	*Quartile 4*	**R-squared**
GIS-derived walkability				
PB500m	-397 (-766 to -28)	-343 (-717 to 31)	-234 (-630 to 163)	0.1093
PB1000m	-632 (-1000 to -264)	-657 (-1029 to -285)	-286 (-689 to 117)	0.1128
LB500m	-320 (-689 to 49)	-352 (-725 to 22)	-241 (-637 to 155)	0.1090
LB1000m	-516 (-884 to -148)	-650 (-1022 to -279)	-257 (-661 to 148)	0.1121

	Odds of ≥ 1 hour/week of utilitarian walking			
	Quartile 2	*Quartile 3*	*Quartile 4*	**Pseudo R-squared**
GIS-derived walkability				
PB500m	1.13 (0.91 to 1.39)	1.41 (1.14 to 1.76)	1.66 (1.31 to 2.11)	0.0475
PB1000m	1.16 (0.94 to 1.43)	1.36 (1.10 to 1.69)	1.62 (1.27 to 2.06)	0.0461
LB500m	1.09 (0.89 to 1.35)	1.30 (1.05 to 1.62)	1.62 (1.28 to 2.06)	0.0465
LB1000m	1.13 (0.91 to 1.39)	1.36 (1.10 to 1.69)	1.73 (1.36 to 2.21)	0.0478

	Odds of ≥ 6 hours/week of utilitarian walking			
	Quartile 2	*Quartile 3*	*Quartile 4*	**Pseudo R-squared**
GIS-derived walkability				
PB500m	0.84 (0.63 to 1.10)	0.78 (0.59 to 1.04)	1.18 (0.89 to 1.56)	0.0173
PB1000m	0.77 (0.58 to 1.01)	0.78 (0.59 to 1.04)	0.97 (0.73 to 1.29)	0.0157
LB500m	0.78 (0.59 to 1.03)	0.84 (0.64 to 1.11)	1.15 (0.87 to 1.52)	0.0168
LB1000m	0.85 (0.64 to 1.12)	0.78 (0.59 to 1.03)	1.11 (0.83 to 1.47)	0.0162

[a] Quartile 1 served as the reference; PB500m (500-m polygonal network buffer), PB1000m (1000-m polygonal network buffer), LB500m (500-m line-based buffer), LB1000m (1000-m line-based network buffer); Models were adjusted for age, gender, body mass index, married/common-law, income, children, immigrant, mood disorder, perceived health, ever smoker, and season.

File 3. Odds of ≥6 hours/week of utilitarian walking (Odds Ratio, 95% CI) in univariate, partially adjusted and fully adjusted models across quartiles of the neighborhood walkability measures of interest (n=2949).[a,b]

	Odds of ≥ 6 hours/week of utilitarian walking			
	Quartile 2	*Quartile 3*	*Quartile 4*	**Pseudo R-squared**
GIS-derived walkability				
Model 1	0.87 (0.66 to 1.15)	0.86 (0.65 to 1.13)	1.42 (1.10 to 1.84)	0.0063
Model 2	0.85 (0.64 to 1.12)	0.82 (0.62 to 1.09)	1.35 (1.05 to 1.75)	0.0119
Model 3	0.84 (0.64 to 1.11)	0.81 (0.61 to 1.07)	1.25 (0.95 to 1.63)	0.0163
Model 4	0.84 (0.63 to 1.10)	0.78 (0.59 to 1.04)	1.18 (0.89 to 1.56)	0.0173
Walk Score				
Model 1	0.65 (0.48 to 0.87)	1.02 (0.78 to 1.34)	1.43 (1.11 to 1.84)	0.0112
Model 2	0.63 (0.47 to 0.84)	0.99 (0.75 to 1.30)	1.36 (1.05 to 1.76)	0.0165
Model 3	0.63 (0.47 to 0.84)	0.95 (0.72 to 1.26)	1.27 (0.97 to 1.67)	0.0203
Model 4	0.62 (0.46 to 0.84)	0.94 (0.71 to 1.24)	1.22 (0.92 to 1.62)	0.0209

[a] Quartile 1 served as the reference; GIS-derived walkability index quartiles: <-1.5, ≥1.5<-0.3, ≥-0.3<1.1, ≥1.1; Walk Score quartiles: <22, ≥22<48, ≥48<68, ≥68

[b] Model 1: Unadjusted. Model 2: Adjusted for age, gender, and body mass index. Model 3: Adjusted for age, gender, body mass index, married/common-law, income, children, immigrant, and mood disorder. Model 4: Adjusted for age, gender, body mass index, married/common-law, income, children, immigrant, mood disorder, perceived health, ever smoker, and season.

APPENDIX F│Individual predictors of total accelerometer-assessed daily steps in *Manuscript 4*

Fully adjusted linear regression model for the association between GIS-derived neighbourhood walkability and daily steps in participants of the Canadian Health Measures Survey study (i.e., *Manuscript 4*) (n=2949)

	Change in daily steps (95% CI)[a]
Age, *years*	-20 (-29 to -10)
Woman	-851 (-1115 to -586)
BMI, kg/m^2	-112 (-136 to -87)
Married/common-law	257 (-53 to 566)
Children ≤15 years in household (yes *versus* no)	383 (66 to 701)
Immigrant	-137 (-479 to 205)
Absence of a mood disorder	738 (260 to 1216)
Income ≥ $40,000 (*versus* <$40,000)	658 (326 to 990)
Ever smoker (*versus* never smoker)	-272 (-539 to -6)
Good/very good/excellent perceived health (*versus* fair/poor perceived health)	1437 (985 to 1888)
Spring/summer season (*versus* fall/winter)	800 (520 to 1080)
GIS-derived neighbourhood walkability	
Quartile 1	*REF*
Quartile 2	-397 (-766 to -28)
Quartile 3	-343 (-717 to 31)
Quartile 4	-234 (-630 to 163)

[a] Parameter estimates represent the change in daily steps associated with a one-unit increment in the variable of interest.

APPENDIX G | Supplemental material for *Manuscript 5*

S1 Table. Characteristics of participants who did and did not complete the follow-up survey.

	Complete Follow-up Survey[a] (n=78)	Incomplete Follow-up Survey [b] (n=123)
	mean (SD)	**mean (SD)**
Age, *years*	59.6 (9.9)	60.1 (10.9)
Steps/day	5484 (2456)	5287 (2785)
Body mass index, *kg/m*^{2}	30.2 (5.6)	30.6 (5.6)
Diabetes duration, *years*	9.0 (9.3)	9.7 (7.1)
Participant-reported walkability	0.3 (1.5)	-0.2 (1.9)
GIS-derived walkability	-0.1 (2.2)	0.04 (2.5)
Audit-assessed walkability	0.1 (1.7)	-0.1 (1.7)
Walk Score®	65.1 (21.3)	68.4 (20.1)
	n (%)	**n (%)**
Women	42 (53.9)	52 (42.3)
Married/common-law	52 (70.3)	72 (67.9)
University education	39 (50.0)	39 (31.7)
Annual household income, ≥ *$50,000*	41 (56.9)	36 (34.0)
Ethnicity, *white*	56 (71.8)	83 (67.5)
Immigrant	30 (38.5)	63 (51.2)
Current smoking	9 (12.3)	8 (7.6)
Insulin use	24 (30.8)	42 (34.2)
Depressed mood	18 (23.4)	37 (30.1)
Dog ownership	10 (12.8)	21 (17.1)

[a] Married/common-law (n=74); annual household income (≥$50,000) (n=72); current smoking (n=73); depressed mood, steps/day, participant-reported walkability (n=77).

[b] Married/common-law, annual household income (≥$50,000), current smoking (n=106); steps/day (n=118), GIS-derived walkability (n=122).

S2 Table. Characteristics of the participants that were included and excluded from the final models.

	Included[a] (n=131)	**Excluded[b] (n=70)**
	mean (SD)	**mean (SD)**
Age, *years*	60.5 (10.4)	60.8 (10.9)
Steps/day	5388 (2488)	5317 (2982)
Body mass index, kg/m^2	30.3 (5.8)	30.7 (5.1)
Diabetes duration, *years*	9.8 (8.4)	8.6 (7.2)
Years living at current address	18.4 (12.4)	17.5 (10.7)
Residential self-selection score based on active lifestyle preferences	0 (1.0)	0 (1.0)
Participant-reported walkability	0.01 (1.5)	-0.03 (2.2)
GIS-derived walkability	0.03 (2.3)	-0.1 (2.4)
Audit-assessed walkability	-0.001 (1.8)	0.001 (1.6)
Walk Score ®	68.9 (19.2)	63.7 (22.7)
	n (%)	**n (%)**
Women	63 (48.1)	31 (44.3)
Married/common-law	91 (69.5)	33 (67.4)
University education	50 (38.2)	28 (40.0)
Annual household income, ≥ *$50,000*	53 (45.3)	24 (39.3)
Ethnicity, white	93 (71.0)	46 (65.7)
Immigrant	59 (45.0)	34 (48.6)
Current smoking	12 (9.2)	5 (10.2)
Insulin use	45 (34.4)	21 (30.0)
Depressed mood	37 (28.2)	18 (26.1)
Dog ownership	19 (14.5)	12 (17.1)
Car ownership/regular vehicle access	104 (79.1)	58 (82.6)
Self-reported past participation in regular exercise	106 (80.6)	61 (87.0)

[a] Annual household income (≥$50,000) (n=117); current smoking (n=130); years living at current address (n=57); residential self-selection score based on active lifestyle preferences (n=56); steps/day (n=130).

[b] Married/common-law and current smoking (n=49); annual household income (≥$50,000) (n=61); years living at current address and residential self-selection score based on active lifestyle preferences (n=23); steps/day (n=65); depressed mood, participant-reported walkability, GIS-derived walkability (n=69).

S3 Table. Univariate longitudinal hierarchical linear regression estimates between the covariates of interest and daily steps (n=131).[a,b]

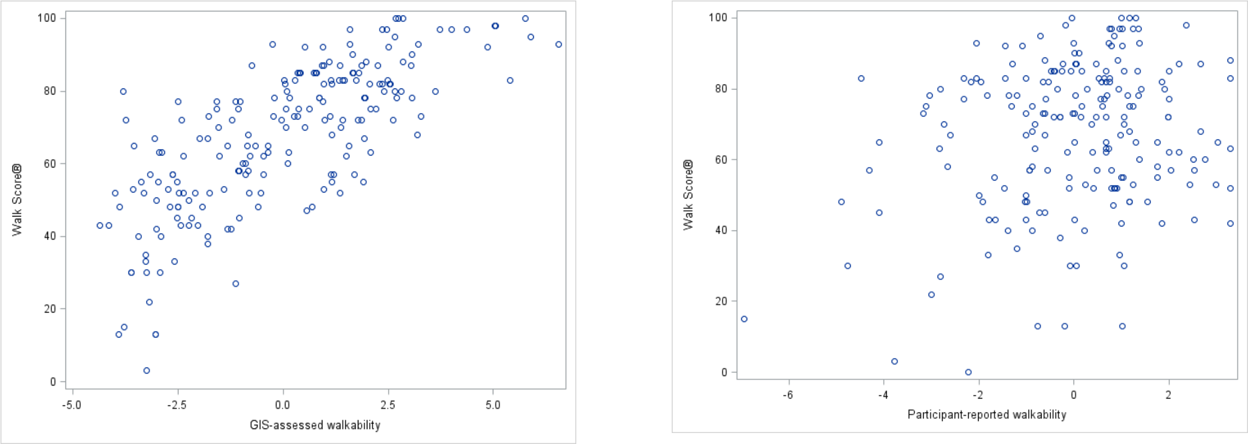
	Change in Daily Steps (95% Credible Interval)
Age, *years*	-96 (-132, -58)
Body mass index, *kg/m^2*	-106 (-176, -36)
Diabetes duration, *years*	-36 (-85, 14)
Years living at current address*, years*	-5 (-54, 45)
Residential self-selection score based on active lifestyle preferences	106 (-552, 761)
Women	-143 (-988, 673)
Married/common-law	838 (-32, 1698)
University education	475 (-384, 1333)
Annual household income*, ≥$50,000*	382 (-480, 1233)
Ethnicity, *white*	-629 (-1549, 273)
Immigrant	682 (-119, 1506)
Current smoking	84 (-1358, 1526)
Regular vehicle access	-1426 (-2752, -118)
Insulin use	-506 (-1376, 375)
Absence of depressed mood	622 (105, 1151)
Dog ownership	1149 (29, 2299)
Spring/summer (*versus* fall/winter)	649 (179, 1124)
Self-reported past participation in regular exercise	1451 (95, 2817)

[a] Annual household income (≥$50,000) (n=117); current smoking (n=130); regular vehicle access (n=67); years living at current address (n=57); residential self-selection (n=56); past participation in regular exercise (n=67).

[b] The univariate estimates for the walkability measures are reported in Table 3 of the manuscript (i.e., *Manuscript 5*).

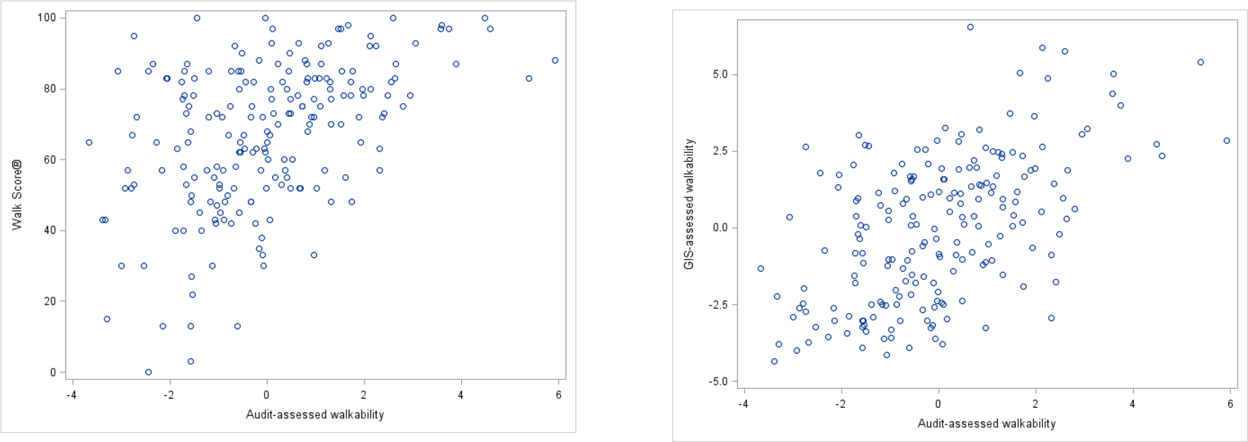
S4 Table. Fully adjusted hierarchical longitudinal linear regression model for the association between participant-reported neighborhood walkability and daily steps (n=131).

	Change in Daily Steps (95% credible interval)
Age, *years*	-106 (-127, -85)
Women	-84 (-492, 331)
Body mass index, *kg/m*^{2}	-119 (-155, -82)
Absence of depressed mood	553 (90, 1023)
Dog ownership	646 (28, 1250)
Immigrant	245 (-167, 655)
Insulin use	-305 (-762, 135)
Spring/summer (*versus* fall/winter)	692 (283, 1106)
GIS-derived neighborhood walkability	27 (-67, 117)
Participant-reported walkability	
Quartile 1	*Reference*
Quartile 2	103 (-457, 677)
Quartile 3	-197 (-774, 395)
Quartile 4	1345 (718, 1976)



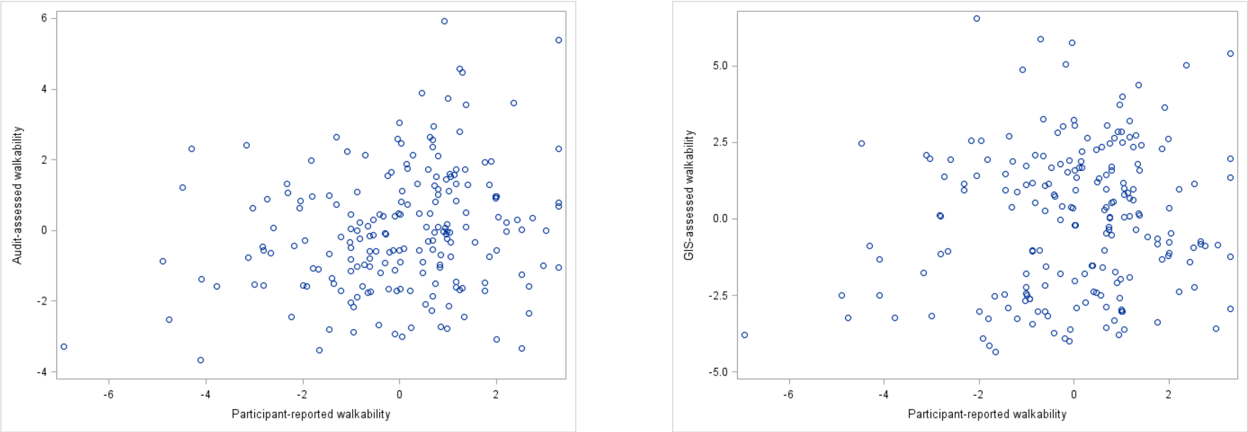
a) GIS-derived walkability *vs.* Walk Score®

b) Participant-reported walkability *vs.* Walk Score®



c) Audit-assessed walkability *vs.* Walk Score®

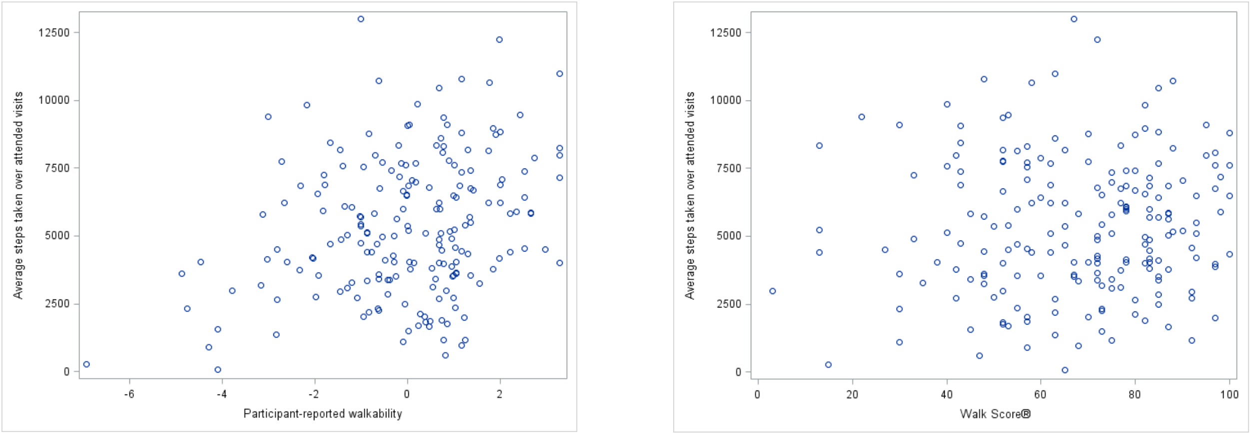
d) Audit-assessed walkability *vs.* GIS-derived walkability



e) Participant-reported walkability *vs.* audit-assessed walkability

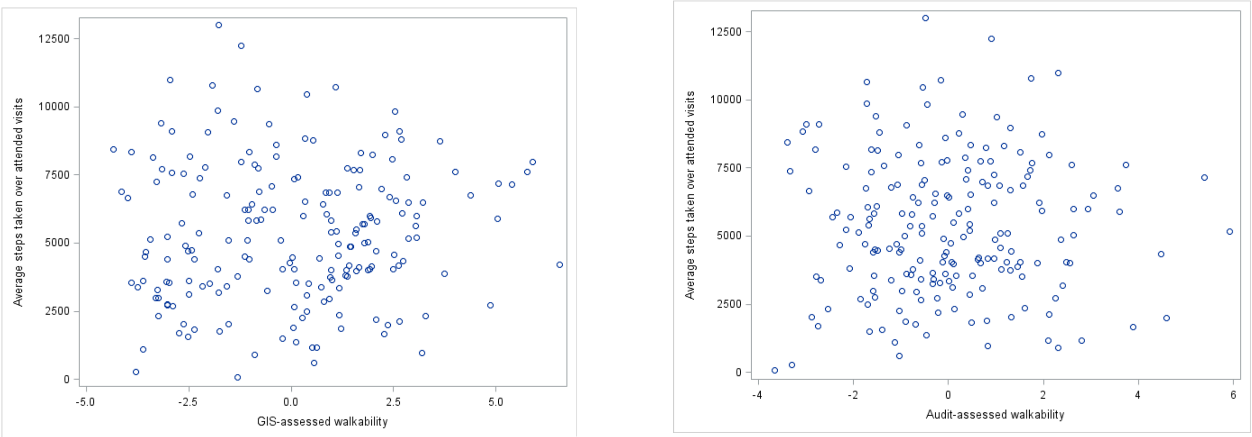
f) Participant-reported walkability *vs.* GIS-derived walkability

S1 Fig. Scatter plots comparing the four walkability measures of interest.



a) Participant-reported walkability *vs.* daily steps

b) Walk Score® *vs.* daily steps



c) GIS-derived walkability *vs.* daily steps

d) Audit-assessed walkability *vs.* daily steps

S2 Fig. Scatter plots of daily steps by each of the four walkability measures of interest.

APPENDIX H │Supplemental material for *Manuscript 6*

Additional File 1. Characteristics of the participants that were retained and excluded from the main analyses.

	Retained (n=97)	All excluded (n=59)[a,b]	Excluded due to missing GPS-accelerometer data (n=45)[c]
	mean (SD)	*mean (SD)*	*mean (SD)*
Age, *years*	59.5 (10.5)	59.9 (10.6)	60.0 (10.5)
Body mass index, *kg/m²*	31.5 (4.5)	32.1 (5.5)	32.4 (5.7)
Time since diabetes diagnosis, *years*	10.3 (7.6)	11.9 (8.8)	13.1 (9.0)
Years at current address	18.9 (13.9)	16.5 (12.3)	16.8 (12.6)
Daily steps	4,980 (2,798)	5,357 (2,867)	4,977 (2,950)
Street connectivity, *number of ≥3 way intersections/km²*	27 (14)	25 (13)	26 (12)
Land use mix (Score range: 0 to 1)	0.30 (0.23)	0.26 (0.17)	0.26 (0.17)
Population density, *population count/km²*	8,915 (8,351)	7,206 (5,939)	7,663 (5,879)
GIS-derived walkability index	0.17 (2.29)	-0.25 (1.77)	-0.25 (1.78)
	%	%	%
Women	43.3	54.2	55.6
Married/common-law	69.1	71.4	68.4
University education	53.6	37.9	40.9
Employed	61.9	53.5	53.3
Immigrant	51.6	45.8	46.7
Depressed mood	30.9	22.4	22.2
Dog ownership	16.5	17.2	17.8
Ever smoker	44.3	43.1	40.9
Insulin use	30.9	35.6	40.0
Car access	74.2	76.8	81.8
Spring/summer assessment (*versus* fall/winter)	40.2	32.2	26.7

[a] Excluded if participant had insufficient wear-time on their multi-sensor devices, GIS land use data were unavailable for their neighbourhoods, the GPS-accelerometer device malfunctioned, or covariate data were missing.

[b] Street connectivity and population density (n=43), land use mix (n=41), time since diabetes diagnosis and regular car access (n=56), married/common-law (n=49), depressed mood, years at current address, university, employed, dog ownership and ever smoking (n=58).

[c] Street connectivity, population density, and land use mix (n=33), married/common-law (n=38), university education, ever smoker, and regular car access (n=44).

Additional File 2. Linear regression estimates for the associations between neighbourhood walkability and total VeDBA accumulated anywhere with corresponding changes in daily steps (n=97).

	Percent change in one SD of total VeDBA (95% confidence intervals)[a,b]	Corresponding change in daily steps (95% confidence intervals)[c]
Model 1	10.6 (-7.4 to 28.6)	168 (-118 to 454)
Model 2	8.6 (-9.3 to 26.4)	137 (-148 to 419)
Model 3	7.2 (-11.4 to 25.7)	114 (-181 to 408)
Model 4	-0.6 (-20.1 to 18.9)	-10 (-319 to 300)
Model 5	0.7 (-13.7 to 15.2)	11 (-218 to 242)

[a] **Model 1:** Unadjusted. **Model 2:** Adjusted for age, BMI, sex. **Model 3:** Adjusted for age, BMI, sex, university, and season. **Model 4:** Adjusted for age, BMI, sex, university, season, car access and residential self-selection. **Model 5:** Adjusted for age, BMI, sex, university, season, car access, residential self-selection and valid wear-time accumulated anywhere.

[b] Effect estimates represent the percent change in one standard deviation of total VeDBA (95% confidence interval) within neighbourhoods (excluding homes) for every one-standard deviation increase in the GIS-derived neighbourhood walkability index. Calculated by multiplying the original estimate by the standard deviation of the walkability index (i.e., 2.16), dividing the result by the SD of the outcome (i.e., 240065.36) and multiplying by 100.

[c] Calculated using the following formula: daily steps=-548+0.0089*total VeDBA occurring anywhere)*(% change in one SD of total VeDBA occurring anywhere/100) where VeDBA occurring anywhere equals one SD of VeDBA occurring anywhere (i.e., 240,065.36)