J Urban Health (2019) 96:583–590
https://doi.org/10.1007/s11524-019-00370-4

Development of a Neighborhood Walkability Index for Studying Neighborhood Physical Activity Contexts in Communities across the U.S. over the Past Three Decades

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Published online: 18 June 2019

Abstract To examine how urban form shapes physical activity and health over time, a measure of neighborhood walkability is needed that can be linked to cohort studies with participants living across the United States (U.S.) that have been followed over the past decades. The Built Environment and Health-Neighborhood Walkability Index (BEH-NWI), a measure of neighborhood walkability that can be calculated for communities across the United States between 1990 and 2015, was conceptualized, developed, and tested using data from the New York City Tri-State Area. BEH-NWI measures were created for 1990 and 2010 using historical data on population density, street intersection density, density of rail stops, and density of pedestrian trip generating/supporting establishments. BEH-NWI scores were calculated for 1-km buffers around the 1990 residences of NYU Women's Health Study (NYUWHS) participants and NYC Department of Health and Mental Hygiene's Physical Activity and Transit (PAT) survey participants enrolled in 2011. Higher neighborhood BEH-NWI scores were significantly associated with greater self-reported walking per week (+ 0.31 MET-hours/week per unit BEH-NWI, 95% CI 0.23, 0.36) and lower body mass index (− 0.17 BMI units per unit BEH-NWI, 95% − 0.23, − 0.12) among NYUWHS participants. Higher neighborhood BEH-NWI scores were associated with

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11524-019-00370-4) contains supplementary material, which is available to authorized users.

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significantly higher accelerometer-measured physical activity among PAT survey participants (39% more minutes of moderate-intensity equivalent activity/week across the interquartile range of BEH-NWI, 95% CI 21%, 60%). The BEH-NWI can be calculated using historical data going back to 1990, and BEH-NWI scores predict BMI, weekly walking, and physical activity in two NYC area datasets.

Keywords Body mass index · Physical activity · Urban design · Environment · Geographic information systems

Abbreviations

API	Application programming interface
BMI	Body mass index
CTOD	Center for Transit-Oriented Development
GEE	Generalized estimating equation
IQR	Interquartile range
Km	Kilometer
MET	Metabolic equivalent task
NYC	New York City
NYCDoHMH	New York City Department of Health and Mental Hygiene
NYCNWI	New York City Neighborhood Walkability Index
NYS-ALIS	New York State Location Information System (NYS-ALIS)
NYUWHS	New York University Women's Health Survey
PAT	Physical activity and transit
SIC	Standard Industry Code
BEH-NWI	Built Environment and Health-Neighborhood Walkability Index

Introduction

Neighborhood walkability refers to built environment features that promote pedestrian activity. In the urban planning literature, these features are sometimes referred to as the "D variables"—*density* of population or residences, *design* of street and transit networks, and *destination* accessibility. [1–5] Higher residential neighborhood walkability has been associated with more walking, higher overall physical activity, lower body mass index (BMI), lower incidence of diabetes, and improved glycemic control among residents [4, 6–14].

However, causal inference in this literature remains limited because there have been few longitudinal studies with repeated measures of neighborhood walkability and health behavior and outcomes [11, 14–16]. While large cohort studies with long-term follow-up, residential address history, and health outcomes are available, the lack of neighborhood walkability measures with the same temporal and geographic coverage limits the use of these cohorts to study how urban form shapes health [17, 18]. The primary difficulty is the lack of retrospective data on a key dimension of walkability: destination accessibility. Some walkability measures, including the widely used index created by Frank et al. and adapted for our New York City Walkability Index (NYCWI), operationalize destination accessibility as land use mix measured using tax-lot data [1, 9, 18, 19]. However, reliance on tax-lot data presents several challenges; there is not a single national clearing house for these data, such data are not available in many communities, they are rarely available historically over the past decades and when available are collected using different methods and coding across different towns and cities [1, 9, 18, 19]. Other walkability measures operationalize destination accessibility as the density of businesses and other local resources. WalkScore, the most prominent measure incorporating destination density, was created for the real estate industry and is now used in health research; it is available nationally but not retrospectively [18].

Here, we address the need for a neighborhood walkability measures that can be calculated uniformly across communities in the U.S. and historically over the past decades. The Built Environment and Health Research Group conceptualized and sourced data for a new measure of neighborhood walkability that utilizes data sources with national coverage and that are available over the past two or more decades.

Development of the New Index

The Built Environment and Health Research Group Neighborhood Walkability Index (BEH-NWI) has four dimensions grounded in urban planning literature describing urban form features that promote walking as a mode of transport [1–5]. The first dimension is *population density*, which promotes pedestrian activity by supporting the concentration of social contacts, goods, services, and public transit in close proximity. The second is *access to public transit*, measured here as access to rail transit, which supports independence from private automobiles and promotes pedestrian activity [19, 20]. The third is *intersection density*, specifically the density of three or more way street intersections, an indicator of street network connectivity, which supports pedestrian activity by allowing more direct walking routes [5, 13]. The fourth is *destination accessibility*, measured here as the density of businesses, institutions and municipal resources that serve as destinations for pedestrian trips or that contribute to a pleasant, lively, or interesting pedestrian experience [5, 11]. Importantly, data sources exist that allow these features of the built environment to be measured uniformly across communities in the U.S. and historically. As with other walkability indexes, to combine the four density measures into a single composite index, the data for each measure is Z-score transformed across the observed spatial units and the four Z-scored transformed measures are summed [1, 9, 19].

Data Sources and Considerations for Estimating the BEH-NWI

Population Density Population counts can be estimated using the Decennial Census data and the American Community Survey data. To estimate population counts in non-Census years, interpolation methods using Decennial Census and American Community Survey data can be employed [21–23].

Density of Rail Transit Stops For studies of single municipalities or regions, data from local transit authorities may be appropriate; for studies considering wider geographies or that have multiple rail systems, we have built a national rail transit stop dataset. The Center for Transit-Oriented Development (CTOD) compiled the Transit-Oriented Development (TOD) database which documents the location of all rail transit stops in the U.S. as of 2011. Using information from municipal transit agencies and other sources, we have augmented the TOD database by adding in stops that closed before 2011 and adding data on when stops opened and closed.

Intersection Density Street network GIS shape files exist going back to the 1990s; however, the spatial accuracy and network connectivity data of older street network shape files, particularly those created before 2003, are often poor, as shown in an example in Fig. 1. Thus, with older street network shape files, street segment intersections and intersection valence often cannot be accurately identified using GIS tools. Therefore, when estimating street intersection density for a given year, there is a trade-off between the higher spatial accuracy of the data contained within a more recently produced shape file and the possibility that the more recent shape file contains street segments that did not exist in the

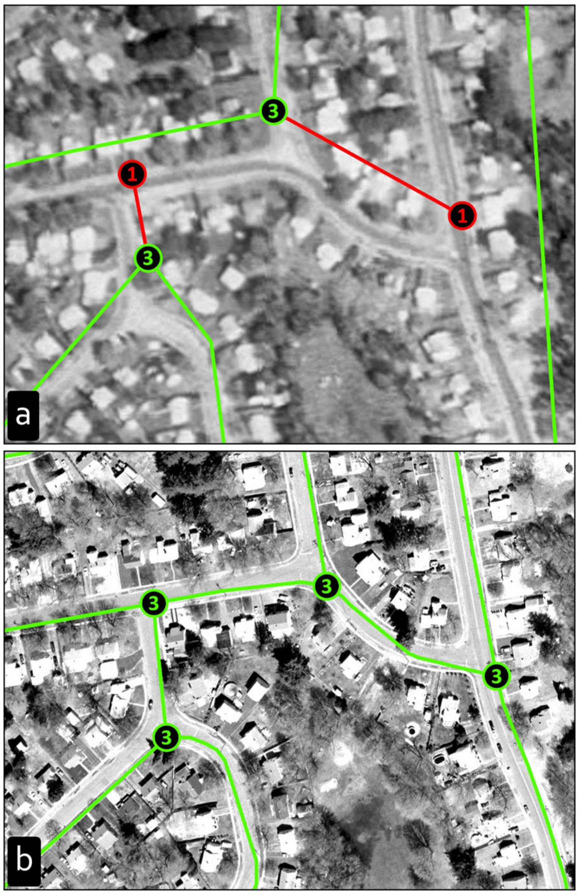

Fig. 1 Street network shape file data and aerial imagery from Connecticut. **a** Available street network data from 1990 and aerial imagery from 1990 for a neighborhood in Connecticut. **b** The same location with street network data from 2003 and aerial imagery from 2004. Overall, in **a**, the street network data are poorly registered with the layout of the streets seen in the aerial images. The red street segment lines and intersection nodes indicate instances where the network data does not reflect the connectivity of the streets shown in the aerial imagery and standard GIS tools for measuring intersection density would produce incorrect results. Analyses of the 1990 street network shape file would identify two, three, or more way intersections in 1990, while analyses of the 2003 shape file would identify four such intersections, which is consistent with the 1990 areal imagery. The higher spatial and network connectivity accuracy of the more recent street network shape file may provide more accurate estimates of intersection density for an earlier time period, than a shape file from the earlier period

earlier period of interest. The extent of the trade-off between the spatial accuracy of the data and the year represented by the data depends on the extent to which a community has built or demolished roads between the year of interest and the year the shape file reflects.

Destination Accessibility The National Establishment Times Series (NETS) is an annual census of establishments—including businesses, nonprofits, and public-sector organizations—in the Dun and Bradstreet database for each year from 1990 onwards [11, 24, 25]. The Dun and Bradstreet database includes all establishments that have a DUNS number and is considered to be exhaustive [25]. We have taken a broad view of what type of establishments contribute to destination accessibility and include establishments that likely serve as destinations that fulfill resident's daily, weekly, or monthly needs (e.g., grocery stores, restaurants, banks, comic book stores) and also establishments that contribute to a pleasant, lively, or interesting pedestrian experience (e.g., art galleries, specialty boutiques). The NETS includes at least one eight-digit Standard Industrial Classification (SIC) number for each establishment and we compiled a list of SIC numbers that reflected our conceptualization of destinations that would promote pedestrian trips. Operationally, pedestrian trip-generating/supporting establishments were defined as all establishments in a neighborhood area, except establishments with SIC codes indicating business-to-business commercial activity and establishments engaged in light to heavy industrial activity (see Online Supplemental material). Establishments were classified as contributing to destination accessibility based on their primary SIC code only.

Application of the Index

Two analyses were conducted to evaluate the BEH-NWI as predictive of physical activity of residents of the New York City Tri-State Area in 2010 and 1990. The first compared the extent to which the BEH-NWI, NYCNWI, and WalkScore data predict physical activity among participants of the NYC Physical Activity and Transit (PAT) survey of 2011. The second assessed whether the BEH-NWI calculated for circa 1990 across the NYC Tri-State Area predicts walking activity and BMI among New York University Women's Health Study (NYUWHS) participants at enrollment into the study.

Methods

Study Populations

Physical Activity and Transit (PAT) Survey: Data on accelerometer-measured physical activity were analyzed from the PAT survey of New York City residents conducted by the New York City Department of Health and Mental Hygiene (NYC DOHMH) [13, 26]. As described in detail elsewhere, PAT survey participants were recruited via random digit dial telephone survey methods (land line and cell phones) and 679 PAT participants completed 4 days or more of physical activity monitoring using ActiGraph GT3x triaxial accelerometers in March through November 2011 [13, 26]. Accelerometer data on minutes of vigorous activity were multiplied by two and added to minutes of moderate activity to estimate "moderate-equivalent minutes" of physical activity per week [13, 26, 27]. The residential neighborhood was defined as a 1-km radial buffer around study participants' homes [13].

New York University Women's Health Study (NYUWHS): Data on engagement in walking and self-reported height and weight were collected in the baseline questionnaires provided by 14,274 women, ages of 34 and 65 years who enrolled in the NYUWHS between 1985 and 1991 [28]. At enrollment, NYUWHS participants resided in NYC Tri-State Area (southern New York State—including NYC, and nearby parts of New Jersey and Connecticut). A 1-km radial buffer around each NYUWHS, participant's residence was defined as their residential neighborhood.

Walkability Measures

New York City Neighborhood Walkability Index

The NYCNWI was adapted from an index developed by Frank and colleagues and has been previously described in detail [4, 8, 9, 13, 19]. As previously reported, the NYCNWI was calculated for 1-km radial buffers around the residential addresses PAT participants' residences using data that reflected built environment conditions in 2010 to 2011 in NYC ($N = 679$) [13].

Estimation of the BEH-NWI in NYC for 2010 and the NYC Tri-State Area for 1990

To calculate the 2010 BEH-NWI for PAT participants, population density was derived from 2010 census data, NYS-ALIS street network data were used to measure intersection density, NYC Metropolitan Transit Authority data were used to measure subway stop density, and destination accessibility was measured using the 2010 NETS dataset. Each of these four measures was calculated for each of the participant's 1-km neighborhood radial buffers, and Z-scores for each of the four measures were calculated across observations. The four z-scores were summed to calculate the final index score for each area unit of observation.

To calculate the BEH-NWI in 1990 for 1-km radial buffers around NYUWHS participants' residences, data from the 1990 census and 1990 NETS were used to estimate, respectively, population density and the density of trip generating/supporting establishments. After evaluating the accuracy of earlier street network files, we based our 1990 three or more way intersection density measure for the NYC Tri-State Area on the 2007 release of the Esri StreetMap Detailed Streets (2003 data ground date). The augmented TOD Database was used to measure the density of subway, light rail, and commuter rail stops within 1 km of each NYUWHS participant's residential address. Each of the four measures were calculated for each NYUWHS participant's neighborhood and Z-scores for each measure were calculated across observed neighborhoods. These Z-scores were summed to calculate the final 1990 BEH-NWI score for each NYUWHS participant's neighborhood.

WalkScore Data

WalkScore data were also used to measure neighborhood walkability for the PAT participants. To preserve participants' privacy, data from PAT survey participants were not sent to the WalkScore.com API [29]. Instead, WalkScore data for the building address closest to each census block centroid in NYC were downloaded from the WalkScore.com API to create a dataset of WalkScores for each census block in NYC. PAT survey participants were assigned the WalkScore corresponding to their census block of residence. A data license and use agreement with WalkScore.com was completed to cover the number of addresses in the PAT survey.

Statistical Analyses

Physical activity in the PAT As previously described, complex survey-weighted linear regression analyses were used to estimate the association between neighborhood walkability and the natural log of minutes of moderate-intensity-equivalent physical activity per week [13]. Analyses controlled for gender, age, income, education, race/ethnicity, self-rated health, number of children in the household, current employment status, neighborhood median household income, homicide rate, and access to parks. Three regression models were fit, the first using the NYCNWI, the second using the BEH-NWI, and the third using WalkScore.com data to measure neighborhood walkability. Each walkability measure was scaled so that a 1-unit difference in each index score represented the interquartile range (IQR) of each neighborhood walkability index. Results from the regression models were expressed as the percent difference in minutes of moderate-intensity-equivalent physical activity per week associated with the IQR of each walkability index.

Walking and BMI in the NYUWHS Linear regression generalized estimating equation (GEE) analyses were used to estimate the circa 1990 association between BEH-NWI and self-reported MET-hours of walking per week and BMI. GEE models used robust standard error estimation procedures to account for potential non-independence of observations for subjects who lived in the same large-scale community area or town. Within the GEE model, clusters were defined as the Community District of residence for NYC residents and town of residence for non-NYC residents. The analyses controlled for participant age, race, education, and smoking status, and the percent of neighborhood residents who were black or African American, and percent of residents with incomes below the federal poverty line.

This work was approved by the Columbia Presbyterian Medical Center and New York University School of Medicine IRBs.

Results

Analyses of Physical Activity in the PAT

All three measures of neighborhood walkability were significantly associated with PAT respondent's measured minutes of moderate-equivalent physical activity per week. The associations between a physical activity and a one inter-quartile range difference in walkability index score were slightly larger for the BEH-NWI (39% difference in minutes of moderate-equivalent physical activity per week across the IQR of BEH-NWI, 95% CI 21%, 60%) and WalkScore (42% difference across the IQR of WalkScore, 95% CI 23%, 65%) as compared with the NYCNWI (30% difference across the IQR of NYCNWI, 95% CI 14%, 46%). However, the confidence intervals for all three estimates largely overlapped.

Analyses of Walking Activity and BMI in the NYUWHS Circa 1990

MET-hours/week of walking reported by the NYUWHS participants was significantly higher across higher quartiles of neighborhood walkability, with MET-hours/week of walking being significantly higher in quartiles 3 and 4 as compared to quartile 1 of the BEH-NWI (see Table 1). The mean BMI for BEH-WHS participants was significantly lower across increasing quartiles of neighborhood walkability, with BMI being significantly lower in quartiles 3 and 4 as compared to quartile 1 of the BEH-NWI (see Table 1).

Discussion

The BEH-NWI is grounded in the urban planning literature describing urban form features that promote walking as a mode of transport, including population density, access to public transit, intersection density, and access to businesses and community resources (destinations) that allow residents to meet needs by walking [1–5]. The BEH-NWI uses datasets that are available nationally and over two or more decades allowing neighborhood walkability measures to be estimated for research study subjects who live across multiple communities and/or for whom historical residential address data are available. This index can support longitudinal analysis of neighborhood walkability in geographically dispersed, historical, or contemporary cohort studies where participant data on physical activity, BMI, or health outcomes have been collected at multiple time points. A walkability measure that can be estimated for neighborhoods at many time points across decades will allow researchers to study changes in behavior occurring in response to changes in neighborhood walkability, either due to study subjects moving residences or due to neighborhood changes that occur around study subjects who stay in place [11]. The BEH-NWI would also be useful in studying associations between neighborhood walkability and physical activity in serial cross-sectional national datasets such as the Behavioral Risk Factor Surveillance System or National Health and Nutrition Examination Survey. The analyses presented here for the NYC Tri-State Area in 1990 and 2010 demonstrate the use of this measure in two historical cross-sectional datasets. The results suggest that the BEH-NWI will be a useful tool for neighborhood built environment health effects research, although further studies of this index in other regions are needed.

This work focuses on the NYC and nearby areas of New York State, New Jersey, and Connecticut and does not consider variation in urban form in other regions. The data used to calculate the BEH-NWI are available nationally and further research is needed to validate that the BEH-NWI is associated with walking, physical

Table 1 Associations between BEH-NWI walking activity and body mass index (BMI) among NYUWHS study participants in 1990

	Coefficient (95% CI) by BEH-NWI quartiles				Coefficient (95% CI) *P* value per one-unit increase in BEH-NWI
	Q1	Q2	Q3	Q4	
N	2857	2707	2670	2854	
Difference in walking (MET-hours/week)[a]	Ref.	0.38 (− 0.10, 0.81)	1.42 (0.81, 1.77)	2.55 (2.04, 2.94)	0.31 (0.23, 0.36) < 0.01
N	3464	3459	3448	3461	
Difference in BMI[a]	Ref.	− 0.09 (− 0.33, 0.15)	− 0.55 (− 0.95, − 0.13)	− 1.42 (− 1.75, − 1.07)	− 0.17 (− 0.23, − 0.12) < 0.01

[a] Adjusted for individual-level factors of age, race, education, and smoking status and neighborhood-level factors percent of residents who were black or African American, and percent of residents whose income was below the federal poverty line

activity, and BMI in a range of rural, suburban, and urban contexts, in a variety of time periods. However, studies across multiple cities of varying urban form have found that measures of residential density, land use mix, street connectivity, availability of destinations, and access to transit are associated with physical activity, pedestrian activity, and lower BMI [4, 9, 11, 30–33]. These prior studies of urban form features that are included in the BEH-NWI suggest that this new index will be useful in multiple contexts across the U.S.

The BEH-NWI uses data on rail transit as a measure of access to public transit. In the NYC Tri-State Area, access to rail transit is an important determinant of a resident's ability to be independent of private automobiles for transportation and this is the case for several other major cities in the U.S. However as a result, the BEH-NWI does not capture the utility of buses, which are the major component of public transit in other areas of the country. Conceptually, a bus stop density measure could be incorporated into the index either as a fifth measure or to replace rail transit. Unfortunately, we are not aware of a database of bus routes that is national in scope and has historical data.

In conclusion, the BEH-NWI can be a valuable new resource for research on how urban form and built environments affect physical activity, obesity, and health. The Index is grounded conceptually in urban planning/design theory and uses data that are available nationwide and historically as far back as 1990. The BEH-NWI addresses the need for a measure that can be utilized with geographically dispersed study populations and/or with cohorts that have been followed over time for health outcomes. This measure will allow researchers to leverage existing cross-sectional and longitudinal human health datasets for new insight into the role of neighborhood features in shaping health.

Acknowledgements Grants and financial: Drs. Rundle, Lovasi and Neckerman were supported by National Institute on Aging grant R01AG049970-03.

Drs. Rundle and Neckerman and Mr. Quinn were supported by the Columbia Population Research Center, which is funded by the Eunice Kennedy Shriver National Institute of Child Health & Human Development of the National Institutes of Health under Award Number P2CHD058486. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Dr. Neckerman was supported by the Institute for New Economic Thinking, Grant #INO13-00023 "Economic Inequality and Sustainable Transportation Policy".

Dr. Mooney was supported by the Eunice Kennedy Shriver National Institute of Child Health and Human Development grant 5T32HD057833-07.

Drs. Chen, Rahai, and Zeleniuch-Jacquotte were supported by National Cancer Institute grants UM1CA182934 and P30 CA016087 and the National Institute of Environmental Health Sciences Center grant ES000260.

Drs. Bartley and Rundle and Mr. Quinn were supported by CDC's Communities Putting Prevention to Work grants 3U58DP002418-01S1 and 1U58DP002418-01.

Financial Disclosure: Dr. Rundle has served as a consultant for the International WELL Building Institute which works on architectural and urban design to promote health.

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