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Measuring the Built Environment for Physical Activity:

State of the Science

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Abstract

Physical inactivity is one of the most important public health issues in the U.S. and internationally. Increasingly, links are being identified between various elements of the physical—or built—environment and physical activity. To understand the impact of the built environment on physical activity, the development of high-quality measures is essential. Three categories of built environment data are being used: (1) perceived measures obtained by telephone interview or self-administered questionnaires; (2) observational measures obtained using systematic observational methods (audits); and (3) archival data sets that are often layered and analyzed with GIS. This review provides a critical assessment of these three types of built-environment measures relevant to the study of physical activity. Among perceived measures, 19 questionnaires were reviewed, ranging in length from 7 to 68 questions. Twenty audit tools were reviewed that cover community environments (i.e., neighborhoods, cities), parks, and trails. For GIS-derived measures, more than 50 studies were reviewed. A large degree of variability was found in the operationalization of common GIS measures, which include population density, land-use mix, access to recreational facilities, and street pattern. This first comprehensive examination of built-environment measures demonstrates considerable progress over the past decade, showing diverse environmental variables available that use multiple modes of assessment. Most can be considered first-generation measures, so further development is needed. In particular, further research is needed to improve the technical quality of measures, understand the relevance to various population groups, and understand the utility of measures for science and public health.

Introduction

Physical inactivity is one of the most important public health issues in the U.S. and internationally, due to its contribution to premature mortality and economic costs (e.g., medical costs, lost productivity).^{1–3} Increasingly, links are being identified between various elements

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of the physical or built environment and physical activity.^{4–8} The built environment—the physical form of communities—includes land-use patterns (how land is used); large- and small-scale built and natural features (e.g., architectural details, quality of landscaping); and the transportation system (the facilities and services that link one location to another).^{8–11} Together, these elements shape access to opportunities for physical activity. (In this article, the terms *built environment* and *physical environment* are used interchangeably.)

Conceptual models guiding research on built environments and physical activity propose that different domains of physical activity (e.g., leisure, transportation, household) are affected by different environmental attributes.^{12–15} Leisure physical activity may be most affected by access to, and characteristics of, public and private recreation facilities.¹⁶ Transportation physical activity may be most related to the proximity and directness of routes from home to destinations (known as walkability) as well as characteristics of the walking and cycling infrastructure, including sidewalks, bicycle lanes, and trails.⁸ Therefore, to understand the influences of the built environment on physical activity, a wide range of environmental measures are needed.

Studies of the built environment and physical activity have evolved over the past few decades. Early research focused on compliance with supervised exercise programs in relation to proximity to facilities.¹⁷ The next generation of studies examined the impact of the community environment (especially convenience of facilities) on leisure physical activity in various populations.^{18–20} At the same time, transportation and city planning researchers were studying the relationship of land-use patterns to walking and cycling for transportation, using both survey and GIS measures.^{5,9,10} More recently, better measures of the built environment have been developed, and physical activity surveys have become more comprehensive, allowing assessment of specific behaviors such as walking and cycling for both recreational and transportation purposes.^{21,22} These measurement advances have allowed research in the past few years to examine multiple elements of the environment in relation to multiple modes and purposes of physical activity.^{4,5,23–29}

To understand the impact of the built environment on physical activity, the development of high-quality measures is essential.³⁰ Three categories of built-environment measures are being used. Obtained by interview or self-administered questionnaires, the first group of measures examines the extent to which individuals perceive access and barriers to various elements of recreation, land use, and transportation environments. The second set of measures uses systematic observations, or audits, to “objectively and unobtrusively”³¹ quantify attributes of the built environment. A third group of measures involves data from archival (existing) data sets that are often layered and analyzed with GIS. Across all three categories (i.e., surveys, audits, and GIS/archival data) development and evaluation of measurement properties are still at a relatively early stage.

This article provides a description of the state of the science in measuring built-environment attributes believed to be related to physical activity. Instruments were identified through searches of the literature, expert input, and feedback from a 2007 workshop. A critical assessment is provided of perceived measures, observational (audit) approaches, and GIS-derived metrics. Whenever possible, the psychometric properties (i.e., reliability and validity) of measures are described, gaps identified in current science, and recommendations made for future progress. Although the focus is primarily on measures of the physical environment, brief mention is included of other contextual variables that are closely intertwined (e.g., crime, social environment, policy variables).^{32,33}

Perceived (Self-Reported) Environment Measures

Evidence on the association between the built environment and physical activity behavior is derived mostly from self-report data on individuals' perceptions of their environments.^{4,34} More than 100 published studies have examined physical activity behavior in relation to perceptions of the environment. The *environment* in these studies includes a combination of the physical (built) environment,^{10,35} social factors,^{33,36} and policy influences.^{37–39} In a recent meta-analysis involving 16 studies,⁷ positive associations were observed between physical activity and several variables, including perceived presence of recreation facilities, sidewalks, shops and services, and perceiving traffic not to be a threat to safety. In the current review, the focus is on survey instruments that are relatively comprehensive (i.e., assess multiple environmental constructs) and that have been tested for psychometric properties (primarily test–retest reliability).

Description of Approach

Several evidence-based frameworks have been developed to aid researchers and practitioners in determining which aspects of the built environment are most likely to influence physical activity (Table 1). Using published evidence, interviews with experts, and Delphi methods, Pikora and colleagues⁴⁰ identified four key environmental domains: functional, safety, aesthetic, and destination, along with nine specific elements within the domains. This conceptual framework has been used to guide development of perceived-environment measures. Ramirez and colleagues⁴¹ used a five-phase expert review process to identify indicators of activity-friendly communities. The Ramirez indicators map reasonably well with the Pikora framework, although the former includes a larger focus on policy-related variables (e.g., local government funding, organizational incentives).

To measure these various indicators, data on the perceived environment have been collected by interviewers (by telephone) and by self-administered methods (in person or by mail). Most often, questions are developed and administered as part of a research project. In other cases, items on the perceived physical environment have been added to surveillance systems, such as the CDC's Behavioral Risk Factor Surveillance System.⁴² Individual responses from these surveys can be aggregated to identify patterns in design and neighborhood features by geographic region, population subgroup, or over time (e.g., lack of access to sidewalks or parks), to determine associations between these design features and physical activity.

Tools and Measures

Table 2 presents a set of tools that measure the perceived built environment.^{29,43–62} Because more than 100 studies of the perceived built environment and physical activity have been conducted,³⁴ it is impractical to summarize all instruments used to date. Those shown in Table 2 cover a variety of populations, administration modes, and levels of detail; each provided adequate descriptions of the process of development and psychometric/measurement properties (primarily test–retest reliability). Our review includes 15 instruments used with adults and 4 instruments that collected data from youth.

Questionnaires ranged in length from 7 to 68 questions. The most commonly assessed variables involved land use, traffic, aesthetics, and safety from crime at a neighborhood or community level. Most of the studies were conducted in mid-sized to large cities. Of the 19 questionnaires examined, four were used with a substantial sample of minority populations.^{29,44,49,53,61} Only one study⁴⁶ presented separate reliability data for urban and rural participants. The tool most frequently used internationally is the Neighborhood Environment Walkability Scale (NEWS),⁴⁷ or the abbreviated version (ANEWS).^{54,56} Use of this tool has been fostered by

collaborations such as the International Physical Activity and the Environment Network (<http://www.ipenproject.org>).

Reliability—Ratings of test-retest reliability have been suggested by Landis and Koch⁶³ in the following categories: 1.0–0.8 (almost perfect agreement); 0.8–0.6 (substantial agreement); 0.6–0.4 (moderate agreement); 0.4–0.2 (fair agreement); and 0.2–0.0 (poor agreement). Using these criteria, the vast majority of questions and scales that reported reliability fell in the substantial or almost perfect range of agreement. In studies where both physical and social factors were measured, the variables in the physical environment tended to show higher reliability than those in the social environment (e.g., safety from crime, social capital).

Consensus is lacking about the applicability of other reliability measures, such as inter-item correlations (Cronbach's alpha) or factor analyses that are commonly used in surveys of beliefs and attitudes. There is little a priori reason to expect conceptually similar environmental variables to co-occur (e.g., parks and trails), so lack of correlation may not reflect a measurement limitation. Conceptually dissimilar items may appear together frequently (e.g., sidewalks and heavy traffic), so alphas and factor analyses may be difficult to interpret. On the other hand, techniques like factor analysis may identify useful groupings of variables.

Validity—Evaluating validity for measures of the perceived environment is challenging and has been comprehensively addressed by only a few studies. Some forms of validity testing require a criterion or gold standard against which to compare a perceived measure. For some attributes of the perceived environment, such as aesthetics, it can be argued that perceptions are the reality.

Three types of validity are most relevant:

1. **Content validity** is the extent to which an instrument measures the appropriate content and represents the variety of attributes that make up the measured construct.⁶⁴ This can be based on formal models, expert opinion, and/or community input. For the perceived measures of the environment, two studies^{40,41} systematically identified the key domains. In these studies, multidisciplinary panels of experts reviewed a large number of constructs, resulting in a set of domains and/or indicators that are empirical and should be considered for measurement development.
2. **Construct validity** is the degree to which a measure “behaves” in a way consistent with theoretical hypotheses⁶⁴ and is predictive of some external attribute (e.g., physical activity behavior). Most validity work on physical activity and the built environment has involved assessment of construct validity. For example, in evaluating ANEWS,⁵⁶ researchers examined individual- and block group-level associations of scores for residential density and land-use mix with walking for recreation and transportation (after controlling for sociodemographic factors).
3. **Criterion-related validity** (sometimes considered a subset of construct validity) is the degree to which a measure is predictive of some gold-standard measure of the same attribute.⁶⁴ For measures of the perceived environment, this may involve the degree which perceptions are correlated with observed or archival data. Nine published studies^{26,28,29,65–71} have compared perceived measures of the built environment with data obtained by observation and/or with GIS-derived measures. All of these studies were conducted in the U.S. (five of nine in the Southeast). Three of the nine studies^{28,29,66} compared perceived measures with audit-obtained data, and eight studies^{26,29,65,67–71} used GIS data as the reference standard. Many different buffer sizes (i.e., the area around a residence) were used in these studies, ranging from 400 meters to 10 miles. The majority of kappa values in these studies

were in the poor to fair range (i.e., from 0.0 to 0.4). Only one study⁷⁰ compared perceived and objectively measured environmental facilities among youth.

Some measures in our review generally had better evidence of criterion validity than did others, but substantial variation also occurred within measures. When participants were asked to report relatively concrete attributes, such as existence of sidewalks or presence of cul-de-sacs, reliability and validity tended to be higher.^{28,69} Perceived crime seemed to have been among the lowest levels of validity.⁷¹ Several explanations have been suggested for the low levels of agreement between perceived and observed neighborhood conditions. It is documented that size of community affects neighborhood perceptions.⁷² Therefore, for some items, the respondents' varying ability to estimate distances accurately is likely to influence concordance with observed measures. This is reinforced in Kirtland et al.²⁹ where decreasing the buffer size increased agreement. Sociologic research on neighborhood evaluation suggests that personal perceptions of the neighborhood environment are only indirectly linked to objective characteristics.⁷³ That is, individual perceptions are derived from filtering objective characteristics through standards of evaluation, which are based on past experiences, aspiration levels, adaptation processes, and individual personality characteristics.⁷³ Thus, the existence of unique situational and personality characteristics indicates that two individuals in the same environment may perceive it differently. Another consideration is that source bias may create spurious associations between self-reported neighborhood conditions and observed conditions (e.g., those with poor health inaccurately report poorer neighborhood conditions).^{32,58}

Skills and Trade-Offs Associated with Using Perceived Measures

Perceived-environment data are collected by interview or self-administration. Both methods of administration present challenges, with a common problem being declining response rates for all types of surveys.⁷⁴ In reliability studies of the perceived environment and physical activity, telephone survey response rates ranged from 31% to 87%.^{74,75} Response rates can be negatively affected by long questionnaires.⁷⁶ Therefore, it is important to select the questionnaire that is as short as possible yet measures what is needed for the project.

Observational Measures (Community Audits)

In addition to perceived-environment measures, researchers have developed instruments and protocols to measure the actual physical environment as it is directly observed.⁷⁷

Description of Approach

Audit tools allow systematic observation of the physical environment, including the presence and qualities of features hypothesized to affect physical activity (e.g., street pattern, number and quality of public spaces, sidewalk quality). Many characteristics of the physical environment can be readily measured without such direct observation, using existing data, such as through GIS or aerial photos (discussed later). Such "remote" methods may be less labor intensive and therefore less time consuming, although no research known to date has directly compared the resources consumed by these various methods. In contrast, researchers use audit tools to collect primary data on physical features that are not commonly incorporated into GIS databases (e.g., street trees, sidewalk width). Audit tools also are used for measuring physical features that are best assessed through direct observation (e.g., architectural character, landscape maintenance).

Not all audit tools are intended for research purposes; some tools were developed to support local decision making. Such tools engage community members in collecting data that will be used to better understand the needs and opportunities for changing the activity environment in their communities. Tools designed for community use are typically less detailed than those designed for research purposes and may not have been assessed for reliability.⁷⁷ This paper

includes a review of the tools that have been published in peer-reviewed sources and are designed primarily for use in research.

Audit tools typically require in-person observation for collecting data (as opposed to videotaping or other methods).¹¹ Researchers walk or drive through a neighborhood, park, or trail, systematically coding characteristics using definitions and a standardized form. For assessing neighborhood or community features, *street segment* is the typical unit of observation. Segments typically comprise two facing sides of one street block. The audit tool itself is usually a paper form containing close-ended questions (e.g., check boxes, Likert scales) and sometimes open-ended questions or comments. Segments are typically sampled because it is not feasible to audit entire neighborhoods, with some exceptions (e.g., Lee et al.⁷⁸). Sampling is either random or purposeful. Purposeful sampling ensures that rare but important features of the environment, such as parks or corner stores, are included. Segments of trails⁷⁹ and areas within parks⁸⁰⁻⁸¹ also can be units of observation.

Tools and Measures

Researchers have developed several audit tools in recent years. Filling a large gap, Active Living Research (a national program of the Robert Wood Johnson Foundation) supported the development of several observational instruments and provides instruments and related information on its website (www.activelivingresearch.org). Separate tools measure community environments (neighborhoods and cities), parks, and trails. Table 3 summarizes key characteristics of 20 audit tools.¹¹⁻⁴⁰⁻⁷⁸⁻⁹⁷ Tools vary significantly in the detail with which they measure various features, from one or two items to dozens of items addressing many distinct characteristics of sidewalks or buildings. Among community audit tools, the Physical Activity Resource Assessment (PARA) tool, Walking Suitability Assessment Form, and Bicycling Suitable Assessment form include less detail. The two park audit tools shown in Table 3 are quite detailed, although the Environmental Assessment of Public Recreation Spaces (EAPRS) Tool is the most extensive (712 items).

Most community audit instruments include one or more measures of: land use (e.g., presence and type of housing, retail); streets and traffic (e.g., traffic volume, presence of traffic calming); sidewalks (e.g., presence and continuity of sidewalks); bicycling facilities (e.g., presence of bike lanes); public space/amenities (e.g., presence of street furniture or benches); architecture or building characteristics (e.g., building height); parking/driveways (e.g., presence of parking garages); maintenance (e.g., presence of litter); and indicators related to safety (e.g., presence of graffiti). Other features of the community environment are observed less consistently. For example, only three community audit tools include measures of noise levels or the presence of dogs, and only one tool (the Analytic Audit Tool) includes measures of health promotion supports (e.g., presence of billboards or other elements promoting physical activity). Additional instruments have been developed to count people in specific settings and contextual information (e.g., accessibility of a facility). For example, reliable observational tools have been developed for school settings (System for Observing Play and Leisure Activity in Youth; SOPLAY)⁹⁸ and parks (System for Observing Play and Recreation in Communities; SOPARC).⁹⁹

Reliability—Inter-observer reliability is the primary form of reliability assessed, although test–retest reliability is relevant for assessing stability of observed features. For community audit tools that report reliability by item or domain, measures of physical disorder/tidiness/safety-related features tend to be less reliable, compared to measures such as land use and street characteristics.

Skills and Trade-offs Associated with Using Observational Measures

In-person observation is time consuming. Researchers must select sites, define and sample segments within sites, train and monitor observers, collect data, enter data, and compute summary variables from voluminous raw data—all of which take time. Estimates of time required for data collection vary depending on the number of items observed, the type of environment (e.g., mixed use or residential only) and how the time required was calculated. For example, observations require 10.6 minutes/segment for the Analytic Audit Tool, and 20 minutes/segment for the Measurement Instrument for Urban Design Quantities.¹¹⁻⁸⁷ Because of the time involved, researchers need to consider carefully whether direct observation is required to answer their research questions or whether existing data (e.g., using GIS) would suffice. Research questions that involve the human qualities of the environment (how a place looks and feels) are especially appropriate for direct observation. The detailed data that can be collected by direct observation can produce results of particular value for those who can act on the findings such as urban designers, landscape architects, and traffic engineers.

As noted in Table 3, audit tools have recently been developed that use personal digital assistant (PDA) devices, such as PalmPilots, or tablet personal computers (PCs) for data collection. PDA-based tools reduce the time required for data entry, as data are automatically entered into software for analysis when collected. PDA devices and tablet PCs also can reduce errors in collecting data by limiting response sets and skipped questions, and can minimize errors that occur in transferring data from paper forms to the computer for analysis. Tools that involve electronic data input should save time for data entry. Among community audit tools that use paper forms, some have a one-page format, which, while not eliminating the need for separate data entry, may be easier to manipulate in the field, compared to multi-page tools.

Relevant skills that are needed for observing the built environment include some knowledge of the content area (e.g., urban planning, recreation studies) as well as the ability to carry out the technical methods of direct observation. Typically, observers are undergraduate or graduate research assistants from various fields (e.g., public health, social science, design, urban planning), who are trained to observe detailed features of the environment. Often recommended is some combination of classroom training (frequently with an illustrated reference manual) and training sessions in the field, in teams and/or individually, to practice measuring elements and to discuss results with a team leader. Because many terms and concepts are likely to be unfamiliar to observers (e.g., setbacks, bollards), the manual and training must provide clear definitions. In each study, observers should be trained until they demonstrate high agreement with the trainer, and inter-observer reliability should be monitored throughout the study to ensure quality of measures.

Selecting from among the available audit instruments requires careful consideration, especially for community audits, where numerous options exist. Researchers should consider factors such as domains and features observed, time required for data collection/data entry, sampling (e.g., all street segments versus a subset), how to manage/aggregate data, instrument reliability (both overall reliability and where available, reliability of specific domains such as land use and the social environment), and ability to compare results with other studies.

Using GIS-Based Measures

Description of Approach

Geographic information systems have much to offer public health researchers interested in the effects of the neighborhood or regional environment on physical activity and obesity. GIS has been defined as the “integration of software, hardware, and data for capturing, storing, analyzing and displaying all forms of geographically referenced information.”¹⁰⁰ GIS-based measures as described here simply refer to measures of the built environment derived primarily

from existing data sources that have some spatial reference (e.g., address or census boundary identification). Using GIS to characterize the built environment is the only feasible way to generate objective measures for studies involving individuals or neighborhoods dispersed across large areas.¹⁰¹ However, problems with existing data mean that care needs to be taken when using GIS, and more research is needed to better assess the reliability, validity, and comparability of GIS-based measures.

The following focuses on using GIS for assessing associations between built-environment characteristics and physical activity. Other applications of GIS to this field, such as for sampling study participants,¹⁰² selecting study areas,¹⁰³ and organizing audit data,²³ are not addressed. More than 50 illustrative studies from the public health and travel behavior literatures are included in this review. Studies using a variety of physical activity–related outcome measures were included (e.g., walking, obesity, vehicle miles traveled, and trail counts).

Measures and Data Sources

The discussion of GIS-based measures of the built environment for physical activity is organized by the following categories that represent the most frequently assessed variables to date:

- population density;
- land-use mix;
- access to recreational facilities;
- street pattern;
- sidewalk coverage;
- vehicular traffic;
- crime;
- other (e.g., building design, public transit, slope, greenness/vegetation); and
- composite variable/index (single variable representing a combination of some of the measures above).

The reviewed studies applied any one or a combination of these measures (Table 4).^{19,104–147} Measures of land-use mix, access to recreational facilities, and street patterns were the most common, followed by population density and composite indices. The main finding from this review was the large degree of variability in the operationalization of measures (Appendix, online at www.ajpm-online.net), making it especially challenging to compare results across studies. The next section briefly describes the GIS-based measures and data sources used in the reviewed studies.

Population density—Population density is one of the most common measures included in studies of the built environment and transportation-based physical activity, primarily because the data for calculating it are readily available (i.e., census and parcel-level data available from government sources [a parcel is an individual plot of land that serves as a sampling unit; data are collected for land ownership records and urban planning purposes]), it is easy to compute, and it has been consistently associated with walking for transportation.^{131,149–151} The most common density measures from the reviewed studies were gross population density (population per total land area) ^{105,109,115,123,125,131,148} and net residential density (in this case housing units per residential acre).^{110,130,139,140,145}

Land-use mix—Measures for the level of mixed land use may be categorized as accessibility, intensity, and pattern measures (Table 5), as described in detail elsewhere.¹⁵² Although some studies have simultaneously correlated multiple measures of land-use mix with physical activity behavior,^{111,132,134,138} it is unclear which measures yield the strongest associations with specific forms of physical activity behavior across populations and settings. Parcel-level data were required to compute many land-use mix measures. These data are derived typically from land ownership records and may be used for land-use planning; however, parcel-level data may be unavailable in some locations and in others may lack detail about land use. For business locations, alternative sources of data included Yellow/White Pages or employment records.

Access to recreational facilities—Measures for access to recreational or exercise facilities can also be categorized as accessibility and intensity measures. There was considerable variability in the types (e.g., some included schools^{69,121,137} and others did not¹¹⁷) or categories (e.g., public or private,^{135,139} free or pay¹⁹) of recreational facilities studied. The Internet and telephone directories were common data sources; however, the search criteria for identifying facilities and the data quality were generally not reported. Most studies used simple calculations to assess distance to nearest facilities or density of groups of facilities. However, Giles-Corti et al.¹¹⁹ progressively adjusted for distance to public open space and its attractiveness and size (e.g., a “gravity measure”) and found stronger associations with use of public open space than the accessibility measures characterized by distance alone.

Street pattern—The number and directness of pedestrian routes may be captured by a variety of GIS-based measures (Table 6) that are described elsewhere.^{153,154} The most common of the reviewed measures was number of intersections per area (or intersection density),^{110,125,132,139,145,148} percentage of 4-way intersections (or connected node ratio),^{104,125,132} and number of intersections per length of street network.^{105,130,140} Although most street pattern measures used data from the street network, a recent study suggested that omitting pedestrian networks (e.g., sidewalks, pedestrian bridges, and park paths) may appreciably underestimate connectivity, particularly in conventional suburban neighborhoods.¹⁵⁵ As pointed out by Forsyth et al.,¹⁵⁶ methodologic issues such as this and others (e.g., determining how to handle freeways or other limited-access roads) can have considerable influence on how street patterns are measured,^{156,157} yet published studies rarely describe how these issues are handled.

Vehicular traffic, crime, sidewalks, and other measures—Data availability for these measures depends on local policies, and these variables often need to be collected by research teams themselves. Measures of vehicular traffic and crime varied, and most data sources are not readily available in all metropolitan areas (Appendix online at www.ajpm-online.net). Measures of sidewalk coverage used mostly existing regional or county databases,^{108,138} with the most common measure being the ratio of sidewalk length to road length.^{108,125,132} Although some cities have an inventory of sidewalks, these data rarely exist in electronic format.¹⁵⁶ The presence of sidewalks and their attributes may be extracted from aerial photos.¹¹⁵ However, the resolution of the images may not be high enough to distinguish details of the sidewalks, and analyses may be time-consuming and error prone.^{132,156}

Other, less frequently used GIS-based measures included indicators of slope,^{68,115,125,138,141} greenness/vegetation,^{67,123} coastal location,¹²⁶ registered dogs,¹²⁹ street lighting,¹²⁹ trees,^{108,138} public transit,¹⁴⁸ regional accessibility,^{108,112} and bike lanes/shoulders.^{108,113} Two studies used GIS-based measures with cluster analysis to classify neighborhoods by themes (e.g., rural working class, new suburban development)¹²⁴ or types (planned unit development, traditional neighborhood development, mixed).¹¹⁴

Composite variables—Eleven studies^{106,110,112,118,133,137,139,144,146,147,159} combined multiple indicators (primarily for land-use mix, density, and street pattern) into a single composite variable or index. Such indices are thought to capture the inter-relatedness of many built environment characteristics, minimize the effect of spatial collinearity, and ease the communication of results.

Three indices were applied to a single metropolitan area^{106,110,112,133,137,139} and three were applied nationally in the U.S. and Canada.^{118,144,146} The neighborhood walkability index developed by Frank and colleagues has been used for studies conducted in Atlanta GA,¹³³ King County WA,¹¹⁰ San Diego CA,^{137,139} and Australia.¹⁵⁹ The number of data sources and degree of computational sophistication varied between studies. Some versions of this index incorporate retail floor area ratio (FAR) as an indicator of pedestrian-oriented design. FAR is the ratio of building square footage to land square footage. Higher numbers indicate that the building is using most or all of the land, and lower ratios suggest much of the land is used for parking. For two indices, only census data were required.^{146,147} In contrast, the Frank et al.¹³³ walkability index required multiple data sources, including parcel-level data, and the Ewing et al.¹¹⁸ regional sprawl index consisted of 22 variables.

Validity and Reliability

The accuracy and completeness of existing data sources,^{156,158,160,161} as well as the geographic scale at which measures are available and aggregated, contribute to the validity and reliability of the GIS-based built-environment measures.

Validity—Validity of GIS-based measures can be thought of as the degree to which the data and measures accurately reflect the real world. Inaccurate and incomplete data represent threats to the validity of GIS-based measures and stem from multiple factors. GIS data are collected for multiple purposes such as managing infrastructure investments and transit systems, collecting taxes, and advertising (e.g., Yellow Pages) and not for conducting research on physical activity.¹⁵⁶ In addition, because the quality of data depends on personnel time and expertise, accuracy varies by region and even municipality. Also, GIS data may come from multiple sources, making errors difficult to identify.¹⁵⁶ Missing-attribute data require that researchers make decisions as to how data may be interpolated (e.g., deriving traffic volume from Annual Average Daily Traffic counts on major roads).^{26,161} The validity of these estimates is unknown.

Temporal concerns may also be introduced if the age of the existing data does not match the timing of outcome measurement. If the study is carried out in a region experiencing major population or environmental change, the GIS-based measures derived from multiple sources (e.g., census, Yellow Pages) and time periods may represent a “reality” that never actually existed.¹⁵⁶ Researchers have addressed such discrepancies by providing evidence that the study area or population has remained fairly constant¹⁴⁰ or by using archival data.¹²¹

Although inaccurate and incomplete data are frequently cited as threats to the validity of GIS data,^{156,158,160,161} the degree to which the errors affect associations with physical activity is unknown. To our knowledge, only one study¹⁶² in this field has validated data from a commercial database with field census. This study compared the presence and types of physical activity facilities from these two sources in 80 census block groups and found only moderate agreement of presence of any physical activity facility (concordance = 0.39 non-urban and 0.46 urban) and poor-to-moderate agreement of physical activity facility type (kappa range 0.14 to 0.76). Most of the errors were due to missing or invalid facilities from the commercial database. Yet, given the random pattern of error and minimal error in the neighborhood-level counts of facilities, associations with physical activity or other health outcomes may be small and probably biased downward. A better understanding of how built-environment measures from

different data sources compare in their association with physical activity would inform prioritization of research-related resources. Such analyses could indicate whether resources could be used efficiently to improve underlying data quality or establish consistent measurement across studies.

The choice of area for aggregating GIS-based measures introduces another source of variation in how environments are characterized and associated with physical activity. Considerable variation exists in the geographic scale used to date (Table 4). Geographic units ranged from administrative boundaries (e.g., census tracts) to buffers of set distances (usually measured “as the crow flies” but can be defined by distance along the street network) around participants’ homes and work places, and this variation likely affects which environmental variables are associated with physical activity.¹⁶³ The use of standardized buffers (e.g., 400 meter radius) to reflect an individuals’ immediate neighborhoods has helped to manage the “modifiable areal unit problem”—a problem of artificial spatial patterning resulting from artificial geographic units of varying sizes and aggregation levels (e.g., census tracts) being imposed on continuous geographic phenomenon (e.g., land-use mix).¹⁶⁴ Yet, there is much debate about the most appropriate buffer size for this research. Using large buffers may mask important within-area variation; 400 meter to 3200 meter buffers have been used commonly, based on the concept of reasonable walking distances. However, the size of the relevant geographic unit may vary by age group and setting (e.g., urban core, suburban), as well as for different built environment characteristics (e.g., land-use mix, access to recreational facilities).¹⁵² The appropriate geographic scale for assessing GIS-based measures requires empirical examination to clarify.^{101,165}

To date, the empirical evaluation of the validity of GIS-based measures comes mostly in the form of construct validity.^{5,165,166} To evaluate the validity of GIS-based measures, it is crucial to conduct more head-to-head comparisons of these measures.^{131,138}

Reliability—The reliability of GIS-based data and measures can be viewed as the extent to which existing data from different time periods for a single area can yield the same measurement values (test–retest reliability), as well as the extent to which two independent analysts can produce the same measurement values (inter-rater reliability). In the case of GIS-based measures, test–retest reliability is partially dependent on how quickly the built environment changes, as well as the consistent maintenance of GIS databases across time, regions, and sources. Neither of these issues has been sufficiently examined.

High inter-rater reliability may be achieved by ensuring that analysts apply similar definitions and data for computing their variables.¹⁵⁶ Unfortunately, such information is rarely provided in sufficient detail to permit replication. The protocols developed by the University of Minnesota, entitled *Environment and Physical Activity: GIS Protocols*¹⁵⁷ and *Environment, Food, and Youth: GIS Protocols*,¹⁶⁷ serve as models for documenting GIS procedures. However, despite detailed documentation, replication can still be limited by the software used to automate computations of GIS measures, which is prone to inconsistent programming between versions (e.g., computing network distances in ArcView), differences in the nature and quality of the raw data, and incomplete documentation.¹⁵⁶

Skills and Trade-offs Associated with Using GIS Measures

Knowing how to obtain, clean, manage, and analyze GIS-based data requires trained personnel and sufficient time to conduct these activities.¹⁶¹ Often there is a mismatch between the variables conceptualized by researchers during a study’s design phase and the messy data encountered by GIS technicians.¹⁵⁶ Yet, the considerable time, expense, and discussions of how these data are rectified to yield clean data for analysis are virtually absent from published studies.¹⁵⁶

Obtaining GIS data can be time-consuming and expensive. Currently, no standardized method of measuring or cataloging these measures and no centralized national repository of such data exist.¹⁰¹ GIS data may be downloaded from the Internet in some regions, but may require contacting government offices and developing written agreements to use the data in other regions.¹⁶¹ For studies that involve multiple jurisdictions, the sources and cost of data may vary. For example, in the Dallas–Ft. Worth TX metropolitan area, the cost in 2007 of parcel-level data ranged from \$0 in one county to \$50,000 in another county. In a study conducted at the University of South Carolina, five additional personnel were hired to assist the research team, and a university lawyer was recruited to ensure the confidentiality of shared data.¹⁶¹ The study costs were nearly double the budgeted costs.

Not all studies relating the built environment to physical activity demand expensive and extensive data and numerous research staff. Many of the reviewed studies were conducted in metropolitan areas with well-maintained and detailed built-environment data, such as Portland OR,⁶⁶ San Diego CA,^{137,139} Seattle WA,^{67,116} San Francisco Bay Area CA,^{107,111} and Minneapolis–St. Paul MN.^{113,132} Other studies relied primarily on available census data for measuring walkability,^{118,146} or limited the number of GIS-based measures, for example, studies of leisure-time physical activity focused on access to recreational facilities. These options may conserve time and expenses associated with acquiring and analyzing data, but they may come at a cost in terms of the accuracy, completeness, and specificity of the neighborhood measures, as well as the generalizability of results.

Challenges and Future Directions

This first comprehensive examination of built-environment measures of relevance to physical activity has demonstrated a great deal of progress over the past decade. Measures of diverse environmental variables are available that use multiple modes of assessment. Most can be considered first-generation measures, so further development is needed. Numerous challenges were identified in three broad categories, and overcoming them will require concerted effort and dedicated funding.

Technical Improvements in Measures

The complexity of the built environment constructs targeted by these first-generation measures and the resulting long lists of variables is a major impediment to widespread use and efficient analysis, especially for observational measures. Most of the reviewed measures reflected an approach of collecting many variables hypothesized to be related to physical activity. As a result, both the perceived and observed variables are sometimes difficult to analyze. But before current measures can be simplified, they must be used in multiple studies. Variables repeatedly unrelated to outcomes or found to be redundant with other variables can be deleted to produce more streamlined second-generation measures. This simplification process may be partially counteracted by the inclusion of new constructs or refinement of currently measured variables.

Measurement gaps were identified for all three categories of measures. Lack of clarity about operational definitions is especially problematic for GIS measures, because there is no standardization of raw data across jurisdictions or consensus on approaches to creating variables. Investigators are encouraged to be explicit in reporting operational definitions of variables. Perhaps it would be useful to post technical details of GIS-based computations online or cite specific protocols, such as those by Forsyth et al.¹⁵⁷ The present review revealed a lack of validated self-report measures related to parks, trails, and workplaces, so further development is needed.

The measures reviewed here use a variety of geographic scales. For example, definitions of *neighborhood* or *community* vary, and different GIS-based buffer sizes are used. The most

relevant geographic scale is likely to differ by built environment variable (e.g., walkability, distance to park); behavior of interest (e.g., walking versus biking, transport versus leisure); and population (e.g., age group, those with or without access to automobiles). For GIS measures, it would be useful if more investigators evaluated and reported results using multiple geographic scales (e.g., 0.5-, 1-, 2-, 3-km buffers).

A specific limitation of observed and GIS-derived measures is the difficulty of assessing the quality of environmental features. The difficulty of obtaining reliable reports of simple indicators of quality of such attributes as playground equipment, trail conditions, and street crossing aids illustrates a need for further development of existing measures. Perhaps methods from other fields (e.g., environmental psychology) can be identified that hold promise for application to built-environment measures.

Relevance to Populations, Settings, and Evolving Issues

It is not clear to what extent the existing environment measures are sensitive to the needs of various population groups and settings. It is likely that physical activity barriers and facilitators vary by age, physical abilities, and culture. The lack of relevance of existing measures to rural environments has been acknowledged,^{5,46} and environmental attributes may have different meanings in low- and high-income communities and in youth versus adults. It is most important to ensure that environmental measures are relevant to populations at highest risk of inactive lifestyles and resulting diseases, such as low-income, racial/ethnic minority, older adult, and rural populations. However, it may not be possible for any single measure to be optimal for each subgroup of interest. Thus, use of core measures with adaptations for specific target populations may be a pragmatic solution. Systematic community input is necessary to develop or adapt measures that are appropriate for the population. An important limitation is that most evaluations of measurement properties were conducted in one region, so there is the possibility that limited variability in environmental variables could reduce reliability and validity coefficients. The majority of the measures were designed to assess neighborhood characteristics of most relevance to active transportation. Few surveys were designed to provide detailed assessments of recreational environments, like parks and trails, which are expected to support recreational physical activity.

In the future, it will be important to include socio-political variables in addition to the measures of the built environment covered in this review. More systematic attention to measuring social and cultural environments could lead to improved understanding of their role in enhancing or inhibiting physical activity. Analyses that include variables from multiple levels of ecologic models are expected to be more powerful in explaining behavior.^{168–171} Principles from ecologic models predict interactions across levels, such that built environment attributes may operate differently in various social contexts. Testing such hypotheses requires adequate measurement of both social and built environment variables. In contrast to the rapid development of built-environment measures, there is a void in published measures of policies that govern built environments.^{37,172} This policy-relevant information is a clear research need, because valid measures of the policy determinants of built environments and physical activity have direct relevance for public health planning and evaluation.

Utility of Measures in Practice Settings

The obesity epidemic and the continuing burden of diseases created by the low prevalence of meeting physical activity guidelines creates a public health imperative to discover and implement solutions. In this context, environmental measures must be considered for their use in research studies but also for their public health impact.

The scientific contributions of environmental measures depend on the extent to which they are widely and appropriately used. There are major challenges to using observational and GIS measures. Observational measures require investments in staff, training, travel, data management, and analysis. Capacity is limited for implementing these measures, so changes in funding priorities and provision of training and support for investigators seem to be needed. Similarly, access to GIS technicians, especially with skills relevant to the variables of interest, is limited. Systematic training programs could both build capacity of investigative teams and encourage standardization of approaches. The most fundamental problem with GIS measures is not only the lack of data in many locations, but also the low or unknown quality and completeness of data, the difficulty or cost of access, and the lack of standardization. Spatial measures require different statistical approaches than do familiar public health data,¹⁷³ and the complexity of the measures creates additional challenges, so training and consensus development about the most appropriate analytic approaches are needed.

Geographic information systems data have the potential to be a useful public health surveillance tool, but that potential is largely unrealized. Ideally, the growing evidence of the impact of the built environment on physical activity, obesity, and other health outcomes will lead to the routine collection of the most critical GIS variables for surveillance purposes. However, some public health departments will not have the capacity to collect even the most basic data, so partnerships with transportation, planning, parks and recreation, law enforcement, and housing agencies will likely be required to provide access to data.

“Walkability audits” already are being used by advocacy groups, but simple and reliable measures are not often available for community groups.¹⁷⁴ Simplified observational measures of parks, trails, schools, workplaces, and other settings can be developed from existing measures. Creating practical measures for community groups should be a goal for researchers. The incorporation of reliable and valid observational measures into health advocacy efforts should be encouraged to provide an evidence base for advocacy.

Several self-report measures of community environment variables are available and can be used for research and surveillance. It is unclear which measures, or which variables within measures, are most effective in explaining variance in physical activity and informing public health practice. As research on built environment and physical activity progresses, variables with limited utility can be dropped, but there may be a need to add variables for newly conceptualized variables.

Conclusion

A substantial literature on measurement of the built environment for physical activity now exists. These topics are of importance to both researchers and practitioners.^{175,176} Although limitations were identified for all types of measures, existing measures have stimulated rapid advancements in understanding environmental correlates of physical activity in a variety of populations and settings. Numerous challenges remain, such as continually improving measures, ensuring relevance for diverse population groups, and integrating built-environment measures into public health surveillance and planning systems. Focused attention to the issues raised in this review is likely to move the field forward and contribute to improving public health.

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Appendix: Detailed List of GIS-Based Variables and Associated Data Sources

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
Population Density	No. of residents living in census tracts or census blocks per area (gross population density)	California; Indianapolis IN; Chapel Hill NC; New York City NY; El Paso TX; Puget Sound WA; Minneapolis–St. Paul MN	Census	1–7
	No. of persons in housing units per unit land area in parcels	Minneapolis–St. Paul MN	Census, parcel-level data*	6
	No. of persons in housing units per unit land area in residential parcels	Minneapolis–St. Paul MN	Census, parcel-level data	6
	No. of housing units per residential acre	Buffalo-Niagara Falls NY Metropolitan Area Erie County NY; Atlanta, GA King County WA San Diego CA	Census; parcel-level data; regional land cover data from aerial images	8–12
	No. of residential units in the household parcel	Seattle WA	County’s parcel-level and building-level assessor’s data	13
	No. of persons in housing units plus total employees per unit land area	Minneapolis–St. Paul MN	Census, parcel-level data	6
	No. of housing units as counted by the census, including both occupied and unoccupied units, per unit land area	Minneapolis–St. Paul MN; 10 largest consolidated metropolitan statistical areas in U.S.	Census, parcel-level data	6,14
	Building footprint area divided by area in parcels, excluding vacant or agricultural land uses	Minneapolis–St. Paul MN	Census, parcel-level data	6
	No. of residents and jobs per area	Gainesville FL	Gainesville built environment database	15
	Developed-area population density	San Francisco Bay Area CA	Census Transportation Planning Package, Association of Bay Area Governments’ Land-use File (hectare -level land use)	16
	Mean net residential density within buffer	Seattle WA	County’s parcel-level and building-level assessor’s	13
Land-use mix				
<i>Accessibility</i>	Distance (network and/or	Cincinnati OH;	Yellow/white pages on	13,17–20

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
	straight-line) to closest specified destination(s) (e.g., fast food restaurant, school, shopping center) or groups of destinations	U.S.; Rockhampton, Queensland; Seattle WA; Minneapolis–St. Paul MN; Northern California	Internet, phone book, school district, county parcel-level and building-level assessor's data	
	Accessibility index (from gravity model) comprised of attractiveness and travel time	San Francisco Bay Area CA	Census Transportation Planning Package, Association of Bay Area Governments' Land-use File (hectare -level land use), MIN-UTP (travel times)	16
	Distance to closest neighborhood retail establishments based on North American Industrial Classification System categories (having ≤ 200 workers)	Minneapolis–St. Paul MN	3 rd quarter ES202 employment records coded, geocoded and cleaned by the Minnesota Dept of Employment & Economic Development	21
<i>Intensity</i>	No. of types of businesses (service, retail, cultural, educational, recreation, neighborhood serving/ retail, employment) located in a neighborhood (range from 0 to 7)	Ten largest consolidated metropolitan statistical areas in U.S.	Standard Industry Classification codes in specific area	14
	No. of types of destinations (churches, community centers, libraries, patches, parks, playgrounds, post offices, schools, swimming pools, theaters, banks, bars, grocery stores, and restaurants)	Seattle WA	Washington State Geospatial Data Archive and Urban Form Lab at University of Washington	22
	No. of types of businesses and facilities (department, discount, and hardware stores; libraries, post offices; parks; walking and biking trails; golf courses; shopping centers; and museums and art galleries), ranging from 0 to 7	Pittsburgh PA	Southwestern Pennsylvania Commission databases	23
	No. of types of businesses and no. of establishments of each type, classified as institutional (church, library, post office, bank), maintenance (grocery store, convenience store, pharmacy), eating out (bakery, pizza, ice cream, take out), and leisure (health club, bookstore, bar, theater, video rental)	Northern California	Yellow/white pages on Internet	20
	Commercial floor area /43,560 * commercial land area	Gainesville FL	Property appraiser's database	15
	Percentage of area for different uses (e.g., residential, commercial,	Indianapolis IN	Parcel-level data	4

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
	industrial, special use, park, water, parking lot, and transportation)			
	Percentage of total parcel area in the following: major land uses (commercial, industrial, office, parks and rec, residential, tax exempt, vacant), night time uses, social uses, retail uses, industrial and auto-oriented uses	Minneapolis–St. Paul MN	Parcel-level data	24
	Percentage of total number of parcels (accessible by the street network) that are residential	Buffalo-Niagara Falls NY Metropolitan Area	Parcel-level data	9
	Percentage of total buildings that are nonresidential	El Paso TX	City of El Paso Planning, Research and Development Dept	5
	Gross employment density (no. of employees per area)	Puget Sound, WA; Minneapolis–St. Paul MN	Washington State Department of Economic Security, Puget Sound Regional Council (area of census tracts in acres), Census, parcel-level data	2,6
	Employment per unit land area	Minneapolis–St. Paul MN	Commercial data base, parcel-level data	24
	Retail employment per unit land area	Minneapolis–St. Paul MN	Commercial data base, parcel-level data	24
	Density of employees in major retail subcategories: general merchandise, food stores, eating and drinking places, miscellaneous retail	Minneapolis–St. Paul MN	Commercial data base, parcel-level data	24
	Jobs density	San Francisco Bay Area CA	Census Transportation Planning Package, Association of Bay Area Governments' Land-use File (hectare -level land use), MIN-UTP (travel times)	16
	Presence of shopping mall	Portland OR	Regional Land Information System from assessment and taxation records	25
<i>Pattern</i>	Dissimilarity index as a function of the number of actively developed hectares in the tract and an indicator for whether the central active hectare's use type differs from that of a neighboring hectare	San Francisco Bay Area CA	Census Transportation Planning Package, Association of Bay Area Governments' Land-use File (hectare -level land use)	16
	Entropy index as a function of the proportion of developed land across six land-use types (residential, commercial, public, offices and research sites, industrial, and parks recreation)	San Francisco Bay Area CA; ¹⁰⁹ (2) Minneapolis–St. Paul MN; ¹³³ Puget Sound ¹¹¹	Census Transportation Planning Package, Association of Bay Area Governments' Land-use File (hectare -level land use), ¹⁰⁹ Parcel-level data, ¹³³ King County BALD file (parcel	2,16,24

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
			data) ¹¹¹	
	Mean entropy as the average of neighborhood entropies computed for all developed hectares within each census tract, where neighborhood is defined to include all developed area within 0.8 km of each relevant active hectare	San Francisco Bay Area CA	Census Transportation Planning Package, Association of Bay Area Governments' Land-use File (hectare -level land use)	16
	Land-use diversity factor (for both origin and destination) comprised measures of mixed use entropy, employed resident-to-jobs balance index, resident-to-retail/services balances index, "residentialness" index	San Francisco Bay Area CA	Census Association of Bay Area Governments	26
	Job-residents balance as a function of the number of jobs and residents in a TAZ	Gainesville FL	Gainesville built environment database	15
	Job mix as a function of the number of commercial, industrial, and service jobs	Gainesville FL	Gainesville built environment database	15
	Land-use mix defined as evenness of distribution of square footage of residential, commercial, and office development (see equation in text)	Atlanta GA; King County WA; San Diego CA	Parcel-level land use from County Tax Assessors Data, metropolitan planning organization	8,10,12
	Land-use mix comprised of residential and commercial building area	New York City NY	Tax assessors data	7
	Proportion of dissimilar land uses among grid cells in an area	Minneapolis-St. Paul MN	Parcel-level data	24
	Herfindahl-Hirschman Index, HHI	Minneapolis-St. Paul MN	Parcel-level data	24
Access to recreation facilities				
Accessibility	Proportion of suburb area allocated to public open space	Melbourne, Australia	Open Space 2002 spatial dataset supplied by the Australian Research Centre for Urban Ecology	27
	Distance to (network and/or straight-line) nearest facility (playgrounds, parks, trail, gyms, recreation centers)	Cincinnati OH; Rockhampton, Queensland; Southeastern SC; San Diego CA; Seattle WA; El Paso TX; Arlington MA; Minneapolis-St. Paul MN; San Antonio TX	Variety of data sources, including: health department inventory; ¹⁴³ Internet searches; department of parks and recreation; ⁶⁹ metropolitan planning organization, yellow pages, web sites, phone calls; ¹³⁷ park layer, Puget Sound Regional Council's regional transportation network	5,13,18,19,28-31

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
			data; ¹³⁸ City of El Paso Parks and Recreation Dept, Center for Environmental Resource Management (schools), Online yellow pages listings (gyms); ¹²⁵ and parcel-level data ¹³³	
	Accessibility to public open space (>2 acres) based on gravity model with adjustment for attractiveness (based on observational assessment), distance, and size	Perth, Western Australia	Ministry of Planning	32,33
<i>Intensity</i>	Density of 48 types of recreational facilities based on kernel densities, simple densities, densities adjusted for population density. Recreational facilities did not include school, churches, private facilities, trails not in parks. Stratified by type of facility (e.g., related to team/dual sports) and requirement of facility user fees.	Forsyth County NC Baltimore County MD Manhattan and Bronx boroughs NY	Online yellow page and Internet searches; Departments of city planning and recreation; Other GIS units	34
	No. of recreational facilities (out of 169 facility types falling under schools, public facilities, youth organizations, parks, YMCA, public fee facilities, instruction, outdoor, member, all facilities)	U.S. (N=42,857 block groups)	Commercially purchased set of digitized business records using Standard Industrial Classification (SIC) codes	35
	No. of for-fee indoor exercise facilities, categorized as private (commercial, requiring membership) or public (owned/managed by local authority/council, with pay per session, membership, or club usage), classified as gym, sports hall, and/or swimming pool	England	Commercial database	36
	No. of resources (parks, gyms, recreation center, and/or public school with public access)	Southeastern SC San Diego CA	Internet searches; department of parks and recreation; yellow pages; metropolitan planning organization, yellow pages, web sites	28,30
	No. of private (e.g., fitness clubs, dance studios, skate rinks) and public (parks, schools) facilities	San Diego CA	Yellow page phone books, phone calls, and internet. Schools and public parks obtained from San Diego Assoc of Governments	10
	No. of recreation facilities (parks, gyms, schools, and biking/walking paths)	El Paso TX	City of El Paso Parks and Recreation Dept, Center for Environmental Resource Management (schools), Online yellow	5

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
			pages listings (gyms)	
	No. of exercise facilities (out of 385) that were classified as either free (public parks, sports fields, public recreation centers, colleges & universities, public schools) or pay (tennis/racquet clubs, aerobic and dance studios, membership swimming pools, health or fitness clubs, YMCAs and YWCAs, and skating rinks). Excluded bike and walking trails, private tennis courts, private swimming pools	San Diego CA	Telephone classified directory, local sports and exercise publications and other commonly available sources	37
	Amount of park area (in hectares) accessible by the street network	Buffalo-Niagara Falls NY Metropolitan Area	Unspecified	9
	Acres of park	San Diego CA	Metropolitan planning organization	30
	Presence of park and trail	Portland OR	Regional Land Information System from assessment and taxation records	25
	Percentage of total residential area that is park or non-park recreation area (Park area included nature trails, bike paths, playgrounds, athletic fields, and state, county, and municipally owned parks. Recreational area included ice or roller skating rinks, swimming pools, health clubs, tennis courts, and camping facilities.)	Erie County NY	Parcel land-use data from NY State GIS Clearinghouse	11
	Square meters of green space and recreational space, including woods, parks, sport grounds (not gyms or fitness centers) *, allotments where people grow vegetables, and grounds used for day trips, e.g., zoo and amusement parks	Maastricht, The Netherlands	Existing GIS databases of Statistics Netherlands on land utilization including the amount of green space and recreational space.	38
Street pattern				
<i>Indices</i>	Composite measure of alpha, beta, and gamma indices (measures of the ratio of intersections to street segments)	U.S.	Street centerlines	17
	Composite measures of block size (average of street length, block area, block perimeter)	U.S.	Street centerlines	17
	Walkability score comprised: negative of ave	U.S.	Street centerlines (not explicitly stated)	39

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
	block size; percentage of all blocks having areas of <0.01 square miles; no. of 3-, 4-, and 5-way intersections divided by the total no. of road miles.			
	Pedestrian-/bike-friendly design factor (for both origin and destination) comprised of square meters per block within 1 mi (average), proportion of intersections that are 3-way intersections, proportion of intersections that are 4-way intersections, proportion of intersections that are 5-way intersections, proportion of intersections that dead ends	San Francisco Bay Area CA	Street centerlines	26
	Street characteristics factor (dichotomized as high or low) comprised of the sum of the following dichotomized variables: no. of road segments (link count); ratio of road segments to intersections (link-node ratio); density of ≥ 3 way intersections; census block density	Forsyth County NC; Jackson, MS	Street centerlines	40
<i>Single variables</i>	No. of intersections with ≥ 4 roads	Melbourne, Australia	Street centerlines	27
	Percentage of intersections that are 4-way intersections (connected node ratio)	10 largest consolidated metropolitan statistical areas in U.S.; El Paso TX; Minneapolis–St. Paul MN	Street centerlines	5,14
	Block length	10 largest consolidated metropolitan statistical areas in U.S.	Street centerlines	14
	No. of intersections per length of street network (in feet or miles)	California; Buffalo-Niagara Falls NY Metropolitan Area; Erie County NY	Street centerlines	1,9,11
	No. of intersections per area	AtlantaGA; King County WA; New York City NY; El Paso TX; Minneapolis–St. Paul MN	Street centerlines	5,7,8,10,12
	No. of 4-way intersections per area	Minneapolis–St. Paul MN	Street centerlines	24
	Ratio between airline and network distances to specified destination(s) (e.g., church, office)	Seattle WA; Minneapolis–St. Paul MN	County's parcel-level and building-level assessor's, Puget Sound Regional Council's regional	13

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
			transportation network data; street centerlines	
	Network segment average length	Indianapolis IN	Street centerlines	4
	Percentage of intersections that are cul-de-sacs	El Paso TX	Street centerlines	5
	Average census block area	Minneapolis–St. Paul MN	Street centerlines	24
	Median census block area	Minneapolis–St. Paul MN	Street centerlines	24
	No. of access points	Minneapolis–St. Paul MN	Street centerlines	24
	Road length per unit area	Minneapolis–St. Paul MN	Street centerlines	24
	Ratio of 3-way intersections to all intersections	Minneapolis–St. Paul MN	Street centerlines	24
	Median perimeter of block	Minneapolis–St. Paul MN	Street centerlines	24
	Street miles per square mile	Gainesville FL	Street centerlines	15
Sidewalk coverage				
	Sidewalk length divided by road length	Minneapolis–St. Paul MN; Gainesville FL; El Paso TX	Street centerlines; ¹³³ County's bicycle and pedestrian level-of-service database; ¹⁰⁸ Black and white photos with 1 ft resolution, acquired by Surdex in 1996 and were subsequently bought by the Public Senate Board, available free through the PdNMapa Initiative funded by Paso del Norte ¹²⁵	15,24
	Total length of sidewalks within buffer	Seattle WA	Puget Sound Reg'l Council's transportation network	13
	Percentage of shortest route to closest bus stop with sidewalk; Percentage of shortest route to campus with sidewalk	Chapel Hill NC	Orthophotographic images, NC Secretary of State, Orange County Land Records Office, Chapel Hill Planning Office, and Chapel Hill Transit	3
	Commute time difference without and with taking into account walking/cycling paths information	Chapel Hill NC	Orthophotographic images, NC Secretary of State, Orange County Land Records Office, Chapel Hill Planning Office, and Chapel Hill Transit	3
	Average sidewalk width	Gainesville FL	County's bicycle and pedestrian level-of-service database	15
Traffic				

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
<i>Indices</i>				
	Traffic factor (dichotomized as high or low) comprised of the sum of the following dichotomized variables: mean speed, maximum speed, and majority speed	Forsyth County NC; Jackson, MS	Posted speed limits from the road network file from Forsyth County Tax Office and the Traffic Engineering Division and City Ordinance Book from Jackson, MS	40
	Volume factor (dichotomized as high or low) comprised of the sum of the following dichotomized variables: maximum traffic volume, mean traffic volume	Forsyth County NC; Jackson, MS	Annual Average Daily Traffic counts (interpolated values for roads without counts using Spatial Analyst)	40
<i>Single variable</i>	Distance (network and/or straight-line) to nearest busy street (e.g., ≥ 60 kph)	Rockhampton, Queensland	Unspecified	18
	Mean traffic volume within buffer	Seattle WA	Puget Sound Regional Council's transportation network	13
	No. of crashes involving a pedestrian or bicyclist per population for 10-year period 1993-2002	Forsyth County NC	University of North Carolina Highway Safety Research Center	40
	Street width (excluding sidewalk), likely to affect the volume of traffic and incidents of accidents	Erie County NY	Street centerlines (TeleAtlas)	11
	Busy street barrier, defined as present where at least one of the four busiest streets in Arlington MA would have to be crossed to access the Minuteman Bikeway	Arlington MA	Street centerlines	31
Crime	No. of serious crimes per 1,000 residents per year	Cincinnati OH	Police department's website	19
	No. of emergency police calls per 1,000 residents per year	Cincinnati OH	Police department's website	19
	No. of crimes per 100,000 people (includes both violent and property crimes)	U.S.	Federal Bureau of Investigation	39,41
	No. of violent crimes	San Antonio	Police blotters published daily in a San Antonio newspaper	29
Other				
<i>Slope</i>	Mean slope within buffer	Seattle WA	Unspecified	13
	Any 100 m road segment with $\geq 8\%$ slope	Forsyth County NC; Jackson MS	Digital Elevation Models from United States Geological Survey	42
	Commute time difference without and with taking into account slope information	Chapel Hill NC	Orthophotographic images, NC Secretary of State, Orange County Land Records Office, Chapel Hill Planning	3

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
			Office, and Chapel Hill Transit	
	Average change in elevation (in ft) in a subject's neighborhood. Calculated by subtracting the lowest elevation point from the highest elevation point.	El Paso TX	Purchased from Topo Depot (www.topodepot.com)	5
	Slope of $\geq 10\%$ for a continuous distance of ≥ 100 m along shortest route from home to Minuteman Bikeway	Arlington MA	GIS elevation data	31
<i>Greenness / vegetation</i>	Normalized difference vegetation index (NDVI) For Tilt 2007, calculated mean of the NDVI values within a circle with the same area as the average walkable area defined by GIS Network Analysis (0.4 mi walking distance of residential parcels)	Indianapolis, IN; Seattle WA	Biophysical remote sensing techniques and multispectral imagery acquired by the Landsat Thematic Mapper Plus (ETM+) remote sensing system.; Dataset acquired from Landsat 5 and process for geo-registration, instrument calibration, atmosphere correction, and topographic correction by the Urban Ecology Research Laboratory at the University of WA	4,22
<i>Coastal location</i>	Coastal suburb (Y/N)	Melbourne, Australia	--	27
<i>Dogs</i>	No. of registered dogs	Rockhampton, Queensland	Unspecified	18
<i>Street lighting</i>	Amount of roadway within 20 m of streetlight	Rockhampton, Queensland	City Council from State's electrical supplier	18
	Street lights per length of road	Minneapolis-St. Paul MN	Aerial photos	24
<i>Trees</i>	Percentage of street miles with trees	Gainesville FL	County's bicycle and pedestrian level-of-service database	15
	Total no. of street trees within buffer	Seattle WA	Unspecified	13
	Street trees (trees within an certain distance buffer) per length of road	Minneapolis-St. Paul MN	Aerial photos	24
<i>Transit</i>	No. of bus stops and subway stations per square kilometer	New York City NY	New York City Dept. of City Planning	7
	Distance to nearest transit stop	Minneapolis-St. Paul MN	Street centerlines	24
	Transit stop density	Minneapolis-St. Paul MN	Street centerlines	24
<i>Regional accessibility</i>	Accessibility index as a function of (1) the number of trip attractions in a specified zone for the particular trip purpose and	Gainesville FL	Unspecified	15

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
	(2) interzonal friction factor for particular trip purpose			
	Regional accessibility using total retail employment and gravity model calculation	Central Puget Sound metropolitan area WA	Employment data from Washington State	43
<i>Bike paths and shoulders</i>	Distance to on-street and off-street bike paths	Minneapolis-St. Paul MN	Minnesota Department of transportation	21
	Length of bike path and paved shoulders divided by road length	Gainesville FL	County's bicycle and pedestrian level-of-service database	15
<i>Neighborhood themes / patterns</i>	Used cluster analysis to identify patterns of environmental characteristics and to specify homogeneous, non-overlapping clusters of neighborhoods sharing various meaningful characteristics. Major neighborhood types: (1) rural working class; (2) exurban; (3) new suburban developments; (4) older, upper-middle class suburbia with highway access; (5) mixed-race/ethnicity urban; (6) low SES, inner city. GIS variables included four measures of street connectivity, one measure of access to recreational facilities, two measures of road type, and one measure of crime	U.S.	Street centerlines (street connectivity), commercially purchased set of digitized business records using SIC codes (recreational facilities), Census feature class roads (road types), U.S. Federal Bureau of Investigation Uniform Crime Reporting county-level data from the National Archive of Criminal Justice Data	44
	Used cluster analysis to identify neighborhood themes consisting of (1) planned unit development; (2) traditional neighborhood development; and (3) mixed	Orange County CA	Land-use database from Orange County Administration Office, Census TIGER files	45
<i>Home age</i>	Median year home built	Southwestern PA	Census	14,23
Composite variables				
<i>Neighborhood accessibility</i>	Comprised: (1) density; (2) no. of employees for specific neighborhood retail businesses; (3) block area	Central Puget Sound metropolitan area WA	Census, employment data from Washington State	43
<i>Neighborhood walkability index</i>	Comprised of land-use mix, residential density, and intersection density	Atlanta GA; King County WA; San Diego CA	Census, regional land cover data from aerial images, street centerlines, parcel-level land-use data	8,10,20,30
<i>Walkability score</i>	Comprised of eight variables related to proximity/density of grocery stores and other retail destinations,	King County WA	Assessor's files (parcel), park information, streets, foot/ bike trails, land slope, vehicular traffic, public transit	46

Measure	Definitions	Study areas	Data sources	Examples of studies where applied
	educational parcels, office mixed use complexes, and block size.			
<i>Intensity factor</i>	Comprised: retail store density, activity center density, retail intensity, walking accessibility, park intensity, and population density	San Francisco Bay Area CA	Census; Census Transportation Planning Package; Association of Bay Area Governments	47
<i>Walking quality factor</i>	Comprised: sidewalk provisions, street light provisions, block length, planted strips, lighting distance, flat terrain	San Francisco Bay Area CA	Census; Census Transportation Planning Package; Association of Bay Area Governments. Some indicators from field inventories	47
<i>Sprawl indices</i>	Comprised: residential density (7 variables), land-use mix (6 variables), degree of centering (6 variables), street accessibility (3 variables)	U.S. counties (448) and metropolitan areas (83)	Census, U.S. Department of Agriculture Natural Resources Inventory	41,48
	Comprised: percentage of total population in low density (>200 and <3500 persons per square mile) and high density (≥3500 persons per square mile) census tracts	330 U.S. metropolitan areas	Census	49
	Comprised: proportion of census metropolitan area (CMA) dwellings that are single or detached units, dwelling density, and percentage of CMA population living in the urban core	Canada	Canadian Census of Population	50

* Typically derived from tax assessors records though also used for land-use planning.

Appendix References

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Table 1Factors in the built environment influencing physical activity (Pikora⁴⁰ and Ramirez⁴¹)

Domain ⁴⁰	Elements ⁴⁰	Indicators ⁴¹
Functional	Walking surface	• Availability and accessibility of competitive transport alternatives and infrastructure (e.g., transit, sidewalks, bike lanes)
	Streets	• Availability of local government and highway funds for sidewalks and bike lanes
	Traffic	• Frequency of nonmotorized transportation (variation by trip purpose and/or trip distance)
	Permeability	• Presence of integration between residential and commercial land uses in dense population areas
Safety	Personal	• Presence of protective social factors and absence of social disorder
	Traffic	
Aesthetic	Streetscape	• Presence of attractions and comforts as well as absence of physical disorder
	Views	
Destination	Facilities	• Availability and accessibility of facilities or natural features for activity
		• Availability of local government funds for parks and recreation facilities
Other		• Presence of community-wide campaigns to increase active living

Table 2
Summary of selected instruments measuring the perceived environment for physical activity

Instrument/study name	Year	Country where tested	No. of items	Mode of data collection (sample size)	Domains covered (reliability, r or K)	Notes
Adult Studies						
San Diego scales of home & neighborhood environments and convenient facilities	1997	U.S. (San Diego)	43	Self-administered, in person (110)	From Sallis et al. ⁴³ (test-retest, ICC) Home equipment (0.89) Total neighborhood (0.68) Convenient facilities (0.80)	
U.S. Women's Determinants Survey	1999	U.S.	14	Interviewer, by telephone (199)	From Brownson et al. ⁴⁴ (test-retest, kappa) Characteristics of the neighborhood (0.44–0.84) Easy access to facilities (0.44–0.75) Workplace & school policy (0.67) Local government policy (0.32–0.47)	Ethnically diverse sample of women, including whites, Hispanics, African Americans, Native Americans
Neighborhood Quality Index	2002	Southern Taiwan	15	Self-administered, in person (1084)	From Yang et al. ⁴⁵ (test-retest, r) An overall r of 0.80 was reported Domains included: Security Services and facilities Social capital	
Perceptions of Environment Support Questionnaire	2003	U.S. (South Carolina)	26	Interviewer, by telephone (408)	From Kirtland et al. ²⁹ (test-retest, r) Neighborhood items Access (0.52–0.74) Characteristics (0.42–0.73) Barriers (0.58–0.69) Social issues (0.47–0.56) Use (0.47) Community items Access (0.28–0.56) Barriers (not reported) Social issues (0.31–0.41)	Also tested in U.S. sample ⁴⁶
Neighborhood Environment Walkability Scale (NEWS)	2003	U.S.	68	Self-administered, by mail (106)	From Saelens et al. ⁴⁷ (test-retest, r) Residential density (0.63) Land-use mix diversity (0.78) Land-use mix access (0.79) Street connectivity (0.63) Walking/cycling facilities (0.58) Aesthetics (0.79) Pedestrian/traffic safety (0.77) Crime safety (0.80)	Also tested in Belgium ⁴⁸ and U.S. samples ⁴⁶ Involved one high-walkable and one low-walkable neighborhood

Instrument/study name	Year	Country where tested	No. of items	Mode of data collection (sample size)	Domains covered (reliability, r or K)	Notes
Women and Physical Activity Survey	2003	U.S.	7	Interviewer, by telephone (344)	From Evenson et al. ⁴⁹ (test–retest, ICC) Traffic (0.64) Sidewalks (0.91) Lights at night (0.69) Unattended dogs (0.72) Crime (0.65) Places to walk (0.75) Places to exercise (0.67)	Ethnically diverse sample of women: white, Latina, African American, Native American
Perceived walking environment	2004	Australia (mid sized university)	8	Interviewer, by telephone (80)	From Humpel et al. ⁵⁰ (test–retest, ICC) Aesthetics (0.93) Convenience (0.86) Access to services (0.86) Traffic as a problem (0.73)	Gender-specific analyses showed slightly higher reliability among women than among men
St. Louis Environmental Instrument	2004	U.S.	30	Interviewer, by telephone (99)	Brownson et al. ⁴⁶ (test–retest, ICC) Walking trails Availability (0.92) Safe while walking (0.60) Most liked features of trail (0.19) Least like features of trail (0.58) Safe from crime (0.58) Workplace incentives (0.70) Workplace policy support (0.44) Workplace safe stairways (0.42) Walking/cycling infrastructure (0.51–0.75) Neighborhood surroundings (0.42) Neighborhood safety (0.36–0.80)	Urban–rural differences in reliability identified; most questions more reliable for rural than urban respondents
Neighborhood walking survey	2005	U.S. (Portland, OR)	15	Interviewer, by telephone (582)	From Li et al. ⁵¹ (test–retest, r) Proximity to local facilities (0.56) Safety for walking (0.56) Safety from traffic (0.56) No. of nearby recreational facilities (0.64)	Involved only individuals aged 65 years and older
Perceived physical activity environment	2005	Mississippi and North Carolina	51	Interviewer, by telephone (106)	From Evenson et al. ⁵³ (test–retest, ICC) Access to facilities/destinations (0.16–0.87) Functionality & safety (0.19–0.79) Aesthetics (0.37–0.64) Natural environment (0.34–0.60)	Involved 49% African Americans; presented results by race and gender
Modified NEWS	2005	Australia (Adelaide)	62	Self-administered, by mail (71)	From Leslie et al. ⁵⁴ (test–retest, ICC) Residential density (0.78) Land-use mix diversity (0.88)	Involved one high-walkable and one low-walkable neighborhood

Instrument/study name	Year	Country where tested	No. of items	Mode of data collection (sample size)	Domains covered (reliability, r or K)	Notes
International Prevalence Study of Physical Activity Environmental Module (now called Physical Activity Neighborhood Environment Survey (PANES))	2006	Sweden	17	Self-administered, by mail (98)	Land-use mix access (0.80) Street connectivity (0.74) Infrastructure for walking (0.76) Aesthetics (0.86) Traffic safety (0.62) Crime safety (0.63) From Alexander et al. ⁵⁵ (test, retest, ICC) Residential density (0.95) Access to destinations (0.46–0.81) Neighborhood infrastructure (0.70–0.78) Aesthetic qualities (0.65) Social environment (0.47) Street connectivity (0.71) Neighborhood safety (0.36–0.65) Household motor vehicles (0.98)	Gender differences examined, with no apparent pattern
Abbreviated Neighborhood Environment Walkability Scale (ANEWS)	2006	U.S.	54	Interviewer, by telephone (1286)	From Saelens et al. ⁴⁷ and Cerin et al. ⁵⁶ (test–retest, r) Residential density (0.63) Land-use mix diversity (0.78) Land-use mix access (0.79) Street connectivity (0.63) Walking/cycling facilities (0.58) Aesthetics (0.79) Pedestrian/traffic safety (0.77) Crime safety (0.80)	Multilevel confirmatory factor analysis used to ascertain measurement properties
Neighborhood Physical Activity Questionnaire (NPAQ)	2006	Australia (Perth)	32	Convenience sample, academic staff; Self-administered (82)	From Giles-Corti et al. ⁵⁷ (test–retest, kappa) Destinations-transportation, within neighborhood (0.59–1.0) Destinations-transportation, outside neighborhood (0.75–1.0) Destinations-recreation, within neighborhood (0.56–0.81) Destinations-recreation, outside neighborhood (0.17–1.0)	Compared reliability within and outside the respondents' neighborhood
Multi-Ethnic Study of Atherosclerosis: Measures of Neighborhood Socioeconomic Position	2007	U.S. (MD, NC, NY)	28	Interviewer, by telephone (5988) (120 participants in the test–retest study)	From Mujahid et al. ⁵⁸ (test–retest, r) Aesthetic quality (0.83) Walking environment (0.60) Safety (0.88) Violence (0.72) Social cohesion (0.65) Activities with neighbors (0.73)	Accounted for multilevel effects of individual nesting within neighborhoods
Youth studies						

Instrument/study name	Year	Country where tested	No. of items	Mode of data collection (sample size)	Domains covered (reliability, r or K)	Notes
Children and parents neighborhood perceptions	2004	Australia (Melbourne)	Children (aged 10–12); 7 Parents: 7	Self-administered, in school (children) and by mail (parents) (253)	From Timperio et al. ⁵⁹ (test–retest, ICC) Children: Their beliefs about traffic, strangers, road safety, sports facilities (0.51–0.84) Their parents' beliefs about traffic, strangers, road safety (0.72–0.85) Parents: Perceptions about traffic density, road safety, sports facilities, public transit (with younger children, 0.60–0.89; with older children, 0.63–0.91)	
Modified version of Neighborhood Environment Walkability Scale (NEWS)	2005	Portugal	9	Self-administered, in school (7 th –12 th grade students; $n=1123$)	From Mota et al. ⁶⁰ (test–retest, ICC) Access to destinations (0.36, 0.75) Connectivity of streets (0.58) Infrastructure for walking/cycling (0.79) Neighborhood safety (0.61, 0.75) Social environment (0.41) Aesthetics (0.60) Recreational facilities (0.67)	
The Trial of Activity in Adolescent Girls (TAAG)	2006	U.S.	26	Self-administered, in school (6 th & 8 th grade girls; $n=480$)	From Evenson et al. ⁶¹ (test–retest, kappa) Safety of environment (0.37–0.52) Aesthetics of environment (0.31–0.39) Facilities near home (0.47–0.78) Transportation (0.34–0.55)	Ethnically diverse sample: black, 19%; Hispanic, 14%; Asian, 3%; multiracial, 3.5%
Children's perceptions of the physical activity environment	2006	Australia	29	Self-administered, in school (5 th and 6 th grade boys and girls; $n=39$)	From Hume et al. ⁶² (test–retest, kappa) Access to destinations (–0.08–1.0) Aesthetics (–0.03–1.0) Safety characteristics (–0.07–1.0)	

Table 3
Summary of instruments measuring the observed environment for physical activity

Instrument/study	Year first published	Country of origin	Number of items ^a	Domains covered (reliability)	Method of collecting data	Time required	Notes
Community audits							
Systematic social observation ⁸²	2001	U.S.	45	Ave. inter-rater reliability =0.87 Type and condition of buildings; condition of grounds/undeveloped spaces; indications of block uniformity/territoriality; type of street; presence of graffiti/litter; neighborhood resources; presence/activities of people; types of nonresidential land uses	Paper form	5–10 min per block	
Systematic Pedestrian and Cycling Environmental Scan (SPACES) Instrument ^{40, 83}	2002	Australia	51	Reliability measured as % of items with $\geq 75\%$ agreement between two raters and as kappa statistic. 48 of 67 items have $K \geq 0.4$ Type of buildings/features; walking & cycling surface; street assessment; overall assessment	Paper form (1 page)	Estimate: observers can audit *2 km in 40 min	One of earliest tools; served as basis for several later tools
Neighborhood Active Living Potential ^{84, 85}	2002	Canada	18	Inter-rater reliability >0.90 Three main categories: activity friendliness, safety, density of destinations	Paper form	Not reported	
Walking Suitability Assessment Form ⁸⁶	2003	U.S.	15	Inter-rater reliability of $r = 0.79$ Traffic volume and speed; sidewalk conditions	Paper form (1 page)	Not reported	
Bicycling Suitability Assessment Form ⁸⁶	2003	U.S.	27	Inter-rater reliability of $r = 0.90$ Traffic volume and speed; bike lane characteristics	Paper form (1 page)	Not reported	
Analytic Audit Tool ⁸⁷	2004	U.S.	144	Reliability measured as % of items with $\geq 75\%$ agreement between two raters. ^b Recreational facilities (100%); land-use environment (75%); transportation environment (74%); signage (57%); social environment (56%); physical disorder/aesthetics (29%)	Two versions: PDA and paper form	10.6 minutes/segment	
Physical Activity Resource Assessment (PARA) Instrument ⁷⁸	2005	U.S.	43	Reliability tests of items with $\geq 10\%$ agreement showed $r > 0.77$ Rates resources (parks, churches, schools, sports facilities, community centers, fitness centers, trails) on: location, type, cost, features, amenities, quality, incivilities	Paper form (1 page)	10 min to audit a medium-sized resource	Focus is evaluation of specific facilities
Senior Walking Environmental Audit Tool (SWEAT) ⁸⁸	2005	U.S.	188	Reliability measured by kappa and agreement scores. Overall, acceptable agreement for 67% of items. Reliability reported as $K > 0.6$ or $r > 0.6$	Paper form	17 min/ segment	Focus is walking environments for seniors

Instrument/study	Year first published	Country of origin	Number of items ^a	Domains covered (reliability)	Method of collecting data	Time required	Notes
				Functionality (71%); safety (58%); aesthetics (67%); destination (42%)			
Sidewalk Assessment Tool ⁸⁹	2005	U.S.	5	Reliability measured by kappa statistic. Levelness (0.51); artificial blockages (0.72); natural blockages (0.54); cleanliness (0.47); surface condition (0.41)	Paper form	8–12 min/segment	Community input and participation contributed to tool development.
Irvine–Minnesota Inventory ^{90, 91}	2006	U.S.	176	Reliability measured as % of items with >80% agreement between raters. 77% agreement w/ 3 raters in CA; 99% agreement w/ 2 raters in MN Accessibility; pleasurable; perceived safety from traffic; perceived safety from crime	Two versions: tablet PC and paper form	In CA: 3–4 hours/setting, with 15–20 segments/setting In MN: 20 min/segment, including travel, fieldwork, data entry, and proofing	
Measurement Instrument for Urban Design Qualities ¹¹	2006	U.S.	27	Reliability measured by intraclass correlation coefficients, where 0.4–0.6 ICCs is moderate agreement Visual enclosure (0.585); human scale (0.508); complexity (0.508); transparency (0.499); image-ability (0.494); tidiness (0.421)	Paper form (1 page)	20 min/segment	Uses videotape to record the environment for observation
African American Health Study ⁹²	2008	U.S.	7	Reliability measured by intraclass correlation coefficients and kappa, ranged from 0.58 (air quality) to 0.84 (sidewalks) Street and block face ratings for: housing conditions, presence of security measures, commercial property, noise, litter	Paper form	5 min/block	Included an assessment of construct validity. Rater effects were present.
Active Neighborhood Checklist ⁹³	2007	U.S.	57	Reliability measured by mean kappa statistic Land-use characteristics (0.74); street characteristics (0.69); quality of the environment for pedestrians (0.68); sidewalks (0.58); shoulders and bike lanes (0.58)	Paper form	11.7 min/segment	Designed for use by community members and researchers
Pedestrian Environment Data Scan (PEDS) Tool ⁹⁴	2007	U.S.	36	Reliability measured by kappa statistic (most items). 33/47 have kappa statistic ≥ 0.4 . Environment; pedestrian facilities; road attributes; walking/cycling environment; subjective assessment	Two versions: PDA and paper form (1 page)	3–5 min/ 400 ft. segment	
Environmental supports for people with disabilities ⁹⁵	2007	Canada	18	Reliability measured by kappa statistic Walking surface (0.11); signage (0.66); surroundings (0.32)	Paper form	Not reported	3 items developed specifically for people with disabilities

Instrument/study	Year first published	Country of origin	Number of items ^a	Domains covered (reliability)	Method of collecting data	Time required	Notes
Measures of environmental characteristics ⁹⁶	2008	U.S.	14 variables (# items not specified)	Inter-rater reliability >0.85 Three main categories: street/traffic, sidewalks, aesthetics	Paper form	Not reported	Based on work of Pikora ⁸³
Park Audits							
Bedimo-Rung Assessment Tools–Direct Observation (BRAT–DO) Instrument ⁸⁰	2006	U.S.	135	Reliability measured as % items with $\geq 70\%$ agreement between two raters. Overall domain reliability = 86.9%; overall geographic area reliability = 87.5% Features (97.6%); conditions (91.4%); access (96.8%); aesthetics (87.5%); safety (100%); Includes measurements for activity areas, supporting areas, surrounding neighborhood	Paper form	Not reported	Includes items to measure post-hurricane park damage
Environmental Assessment of Public Recreation Spaces (EAPRS) Tool ⁸¹	2006	U.S.	712	Kappa statistic and % agreement. Most items = good to excellent reliability. Trail/path; specific use; water-related; play elements	Paper form	Not reported	
Trail Audit							
Path Environment Audit Tool (PEAT) ⁷⁹	2006	U.S.	93	Reliability measured by mean K statistic. 15/16 primary amenity items ≥ 0.49 (“moderate”); all had observed agreement $\geq 81\%$. Design; amenity; maintenance	Tablet PC or PDA; GPS unit	Not reported	
Workplace Outdoor Environment Audit							
Workplace walkability audit ⁹⁷	2005	U.S.	Likert, 9 open ended, 5	Reliability measured with weighted K statistic Pedestrian facilities (0.54); pedestrian conflicts (0.67); crosswalks (0.60); maintenance (0.23); path size (0.33); buffer (0.64); universal accessibility (0.48); aesthetics (0.44); shade (0.26)	Paper form	Not reported	

PDA, personal digital assistant

^aNumber of items observed is reported in different ways in publications describing these instruments. Here, number of items refers to the total number of discrete items recorded for each segment or unit of analysis. Identifying information (observer #, segment #) is not included in this count.

^bReliability also measured as intraclass correlation coefficient (ICC) and as Cohen’s kappa statistic.

Table 4
Geographic scale and types of GIS-based measures from selected studies, by outcome type^a

Study	Geographic scale	Population density	Land-use mix	Access to recreation facilities	Street pattern	Sidewalk coverage	Vehicular traffic	Crime	Other	Composite index ^b
Transportation activity outcomes										
Boer (2007) ¹⁰⁴	0.25-mi buffer	X	X		X				X	
Braza (2004) ¹⁰⁵	0.5-mi buffer	X			X					
Cervero (1997) ¹⁰⁶	Census tract									X
Cervero (2003) ¹⁰⁷	1-, 5-mi buffer		X		X					
Ewing (2004) ¹⁰⁸	Traffic analysis zones	X	X		X	X			X	
Frank (1994) ¹⁰⁹	Census tract	X	X							
Kerr (2006) ¹¹⁰	1-km network buffer	X	X		X					X
Kockelman (1997) ¹¹¹	Traffic analysis zones, census tracts	X	X							
Krizek (2003) ¹¹²	150-m grid cells								X	X
Krizek (2006) ¹¹³	^c		X						X	
McNally (1997) ¹¹⁴	Neighborhood								X	
Rodriguez (2004) ¹¹⁵	Commute route	X				X			X	
Tilt (2007) ⁶⁷	0.40-mi network buffer		X						X	
Leisure activity outcomes										
Berke (2007) ¹¹⁶	0.1-, 0.5-, 1-km buffers									X

Study	Geographic scale	Population density	Land-use mix	Access to recreation facilities	Street pattern	Sidewalk coverage	Vehicular traffic	Crime	Other	Composite index ^{a,b}
Diez Roux (2007) ¹¹⁷	0.5-, 1-, 2-, 5-mi buffer			X						
Ewing (2003) ¹¹⁸	County, metropolitan area									X
Giles-Corti (2005) ¹¹⁹	^c			X						
Gomez (2004) ¹²⁰	0.5-mi buffer			X				X		
Gordon-Larsen (2006) ¹²¹	8.05-km buffer			X						
Hillsdon (2006) ¹²²	^c			X						
Lindsey (2006) ¹²³	0.5-mi network buffer	X	X		X				X	
Nelson (2006) ¹²⁴	3-km buffer								X	
Rutt (2005) ¹²⁵	0.25-mi buffer	X	X	X	X	X			X	
Sallis (1990) ¹⁹	1-, 2-, 3-, 4-, 5-mi buffer			X						

Transportation and leisure, or total activity outcomes

Ball (2007) ¹²⁶	Neighborhood			X	X				X	
Cohen (2006) ¹²⁷	0.5-mi buffer		X		X					
Doyle (2006) ¹²⁸	County				X			X		
Duncan (2005) ¹²⁹	0.5-, 1-mi buffer		X	X			X		X	
Epstein (2006) ¹³⁰	0.5-mi buffer	X	X	X	X					
Forsyth (2007) ¹³¹	0.2-, 0.4-, 0.8-, 1.6-km street network, straight-line buffer, 805 X 805-metric grid	X	X							

Study	Geographic scale	Population density	Land-use mix	Access to recreation facilities	Street pattern	Sidewalk coverage	Vehicular traffic	Crime	Other	Composite index ^{a,b}
Forsyth (2008) ¹³²	0.2-, 0.4-, 0.8-, 1.6-km street network, straight-line buffer, 805 X 805-metric grid		X	X	X	X			X	
Frank (2005) ¹³³	1-km network buffer									X
Handy (2006) ¹³⁴	400-, 800-, 1600-m buffer		X							
Hillsdon (2007) ¹³⁵	Super Output Area (England)			X						
Jilcott (2007) ⁶⁹	1-, 2-mi buffer			X						
King (2005) ¹³⁶	1.5-km network buffer, block group		X					X		
Kligerman (2007) ¹³⁷	0.5-mi network buffer			X						X
Lee (2006) ¹³⁸	1-km buffers	X	X	X	X	X	X	X		
McGinn (2007) ⁶⁸	0.125-, 0.5-, 1-mi buffer							X	X	
McGinn (2007) ²⁶	0.125-, 0.5-, 1-mi buffer				X		X			
Michael (2006) ⁶⁶	Neighborhood		X	X						
Norman (2006) ¹³⁹	0.5-, 1-mi network buffer	X	X	X	X					X
Roemmich (2007) ¹⁴⁰	0.5-mi buffer	X		X	X		X			
Troped (2001) ¹⁴¹	N/A			X			X		X	
Wendel-Vos (2004) ¹⁴²	0.3-, 0.5-km buffer			X						

Study	Geographic scale	Population density	Land-use mix	Access to recreation facilities	Street pattern	Sidewalk coverage	Vehicular traffic	Crime	Other	Composite index ^{a,b}
BMI/overweight/obese outcomes										
Burdette (2004) ¹⁴³	Neighborhood		X	X				X		
Ewing (2006) ¹⁴⁴	County							X		X
Frank (2004) ¹⁴⁵	1-km network buffer	X	X		X					
Lopez (2004) ¹⁴⁶	Metropolitan area									X
Ross (2007) ¹⁴⁷	Census tract, census metropolitan area (Canada)									X
Rundle (2007) ¹⁴⁸	Census tract	X	X		X				X	

^aSome studies also included BMI as an outcome variable

^bCombination of two or more built-environment measures from different domains summarized into a single variable

^cDistance to specified destination served as GIS-based measure, where the individual study participant served as unit of analysis.

Table 5Summary of types of measures for land-use mix¹⁵²

Types of measures of land-use mix	Definition	Examples	Comments
Accessibility	Degree to which mixed-land activities are easy to reach by residents	(1) Distance from residential land uses to the nearest nonresidential land use (e.g., retail establishment); (2) gravity-based measures (sum of accessibility of residential land use to all other given types of nonresidential land uses, discounted by the distance decay function between these two points); and (3) gravity-based measures that account for attractiveness and competition of nonresidential land uses	Conceptually simple but range in sophistication and computational burden. Best for individual-level analyses.
Intensity	Volume or magnitude of mixed-land uses present in an area	(1) Counts or densities of specific destinations in an area, and (2) proportion of area devoted to different types of land uses	Entail the least amount of computation and data requirements and are conceptually and computationally simple. Can be implemented at an aggregate- or area-level, which means their value depends on the choice of geographic scale.
Pattern	Degree of evenness of various land-use types in an area	(1) Balance index, (2) Herfindahl–Hirschman index, (3) dissimilarity indices, and (4) entropy measures	Best at capturing diversity, isolation, and clustering of land uses; however, their degree of interpretation and computation varies.

Table 6

Abbreviated list of GIS-based variables and associated data sources

Measure	Examples of definitions	Data sources	Examples of studies where applied
Population density	Number of residents living in census tracts or census blocks per area (gross population density)	Census	105, 109, 115, 123, 125, 132, 148
	Number of housing units per residential acre	Census; parcel-level land-use data *; regional land-cover data from aerial images	110, 130, 139, 140, 145
Land-use mix			
Accessibility	Distance (network and/or straight-line) to closest specified destination (s) (e.g., fast-food restaurant, school, shopping center) or groups of destinations	Yellow/White Pages on Internet, phone book, school district, parcel-level data	127, 129, 132, 138, 143, 134
	Distance to closest neighborhood retail establishments based on North American Industrial Classification System categories (having ≤200 workers)	3rd quarter employment records (from the Quarterly Census of Employment and Wages) that were coded, geocoded and cleaned by the Minnesota Department of Employment & Economic Development	113
Intensity	Percentage of total parcel area for different uses (e.g., commercial, industrial, office, parks and rec, residential, tax exempt, vacant, night-time uses, social uses, retail uses, industrial and auto-oriented uses)	Parcel-level data	123, 132
	Number of types of businesses (e.g., service, retail, cultural, educational, recreation/leisure, neighborhood serving/retail, employment, institutional, maintenance, eating out) located in a neighborhood	Standard Industry Classification (SIC) codes, Yellow/White Pages on Internet	104, 134
Pattern	Entropy index as a function of the proportion of developed land across six land-use types (residential, commercial, public, offices and research sites, industrial, and parks recreation)	Parcel-level data	109, 111, 132
	Land-use mix as a function of the square footage of residential, commercial, and	Parcel-level data	110, 137, 139, 145

Measure	Examples of definitions	Data sources	Examples of studies where applied
office development			
Access to recreational facilities			
Accessibility	Distance to (network and/or straight-line) nearest facility (playgrounds, parks, trail, gyms, recreation centers)	Variety of sources, including health department, Internet searches, department of parks and recreation, metropolitan planning organization, Yellow Pages, phone calls, regional transportation network data, parcel-level data	69, 120, 125, 129, 132, 137, 138, 141, 143
	Accessibility to public open space (>2 acres) based on gravity model with adjustment for attractiveness (based on observational assessment), distance, and size	Metropolitan planning organization	119, 122
Intensity	Number of recreational facilities, often categorized by type (e.g., pay/free, public/private), per area	Variety of sources, including online Yellow Page and Internet searches; departments of city planning and parks/recreation; commercially purchased set of digitized business records using SIC codes; Internet searches; metropolitan planning organization; local sports and exercise publications	19,69, 117, 121, 125, 135, 137, 139
	Proportion of total residential area that is park and non-park recreation area (Park area included nature trails, bike paths, playgrounds, athletic fields, and state, county, and municipally owned parks. Recreational area included ice or roller skating rinks, swimming pools, health clubs, tennis courts, and camping facilities.)	Parcel-level data	140
Street pattern			
	Percentage of intersections that are 4-way intersections	Street center-lines data	104, 125, 132
	Number of intersections per length of street network (in feet or miles)	Street center-lines data	105, 130, 140

Measure	Examples of definitions	Data sources	Examples of studies where applied
Other			
Vehicular traffic	Street width (excluding sidewalk), likely to affect the volume of traffic and incidents of accidents	Street center-lines data (TeleAtlas)	140
Crime	Number of crimes per 100,000 people (includes both violent and property crimes)	Federal Bureau of Investigation	128, 144
Sidewalk coverage	Sidewalk length divided by road length	Street center-lines data; county's bicycle and pedestrian level-of-service database; black and white photos with 1-ft resolution	108, 125, 132
Slope	Any 100-m road segment with $\geq 8\%$ slope	Digital Elevation Models from U.S. Geological Survey	68
Greenness/vegetation	Normalized difference vegetation index	Biophysical remote sensing techniques and multi-spectral imagery	67, 123

* Typically derived from tax assessors records, although also used for land-use planning.