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Community deprivation, walkability, and public health: Highlighting the social inequalities in land use planning for health promotion

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ABSTRACT

International land use planners tend to focus on walkability that could shape both residential behaviors and health outcomes. Understanding the relationships among community deprivation, walkability, and health outcomes will provide insights into appropriate land use planning that supports public health promotion. This paper develops a revised Walk Score tool for measuring community walkability in China. Under the original Walk Score methodological framework, (1) 6 principle amenities (19 items) and their weight (utilization frequency) are first selected by expert panel evaluation and questionnaire survey; (2) a tolerance time approach is then employed to determine the decay function, and the walking travel time from community to each amenity is calculated by using the Baidu Map; and (3) three pedestrian characteristic factors (intersection density, block length, and slope) are considered to adjust the score. We apply the proposed methodology to the case of Shenzhen and discover great variations in walkability among the 8117 communities within it. The high–high clusters are located in the central blocks, while the low–low clusters emerge in the outskirts. Using spatial regression, we observe significant negative associations between community walkability and three health indicators (cardiopathy, hypertension, and liver cancer). It suggests that better health outcomes would be observed in more walkable communities. We further find that children concentrated and socioeconomically disadvantaged communities exhibit lower walkability. These results evidence the significant social inequalities in walkability among the communities of Shenzhen. Path analysis identifies complex linkages among community deprivation, walkability, and public health. For cadiopathy and hypertension, three categories of significant paths are identified: (1) residents in deprived community have worse health outcomes due to lower walkability; (2) poorer health outcomes occur in deprived communities as a result of higher $PM_{2.5}$ exposure; and (3) less walkable communities are exposed to greater $PM_{2.5}$ concentration and deprived communities are generally characterized by lower walkability and consequently have worse health outcomes. We argue that social inequalities in walkability should attract the attention of land use planners. In order to address this pressing issue, three areas should be given priorities in future land use planning: (1) adopting urban form-based zoning schemes; (2) economic inputs for streetscape improvements; and (3) formulating affordable and low-renting housing policies. Findings of this case should generate more generalized knowledge that enhances public health promotion within the land use planning context.

1. Introduction

During the past three decades, non-communicable chronic diseases (NCDs) as well as obesity and overweight have been increasing dramatically across the world (World Health Organization (WHO), 2011). To combat global epidemics of NCDs and reduce obesity and overweight, the WHO and United Nations have advocated the design of built environments as a key strategy that promotes the active living for the entire population (United Nations Organization, 2011; WHO, 2015). Evidence has accumulated that built environments could shape both residential behaviors and health outcomes. In particular, recent international interest tends to focus on walkability and reports that more walkable communities present more active participation in physical activity as well as lower obesity and overweight prevalence. Although prior observations cannot generate causal inference, the Community Guide (http://archived.naccho.org/topics/HPDP/commguide/) has collected sufficient evidence to support a shift towards walkable community planning for recovering the urban quality and promoting active

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commuting. There emerges increasing emphasis on walkability as both a means and an indicator of public health promotion due to its potential as a complementary strategy to curb the rise in NCDs and obesity at population level (Sallis et al., 2012). Hence, strategies in the realms of built environment design to enhance walkability are widely recommended by the public health authorities for communities to become more walkable (US National Physical Activity Plan, 2010; WHO, 2009).

In reality, walkable community design does not fall into the scope of traditional public health responsibilities, but it is a common part of land use planning (Ricklin et al., 2012). Administered and enacted by local governments, land use zoning and plan regulate the physical attributes of built environment and control community design which can promote public health by creating opportunities for healthy living (Ricklin et al., 2012). The specific role of land use planning in public health promotion typically includes encouraging healthy living through access to destinations (e.g., planning for transport and land use that benefit walking, jogging, and active leisure) (Kelly et al., 2014; Saunders et al., 2013; Saelens and Handy, 2008), and increasing opportunities for fresh food access and healthy eating behaviors (e.g., planning for healthy food location and retailing through regulated distributions of supermarkets, grocery store, and organic retailers) (Robinson et al., 2013; Su et al., 2016a). With respect to the walkability, the New Urbanism, a well-known land use planning paradigm, advocates the creation of pedestrian friendly environments that promote walkable communities (Lund, 2003). Additionally, a number of land use plans (Appendix A) place high priorities on change in walkability, including Transportation for America (http://t4america.org), Smart Growth America (http://www.smartgrowthamerica.org), and the National Complete Streets Coalition (http://www.completestreets.org). In this regard, experts and practitioners in land use planning are searching for the practical and robust techniques that help reform land use, building, and zoning codes to achieve more healthy communities.

Recent literature has demonstrated a range of scoring or checklist methodologies to assess the walkability. These approaches typically employ structured interview and authority consulting to determine the evaluation factors and further yield numeric scores that enables the planners to audit communities and routes and identify the isolated neighborhoods whose walkability should be improved. These provide a means of comparing local plans with national standards and capturing the commitment to principles of walkable community design (Godschalk and Rouse, 2015). One example is the Pedestrian Environment Review System (TRL, 2009), which permits comprehensive, systematic, and robust description of walkability for a pedestrian route. Another example is the Walk Score (www.walkscore.com), a publicly accessible website, which calculates a reliable and valid score of community walkability based on distance to amenities. The developed tools have greatly advanced the connection between land use planning and public health promotion. However, conversations are still missing in the literature on three essential issues. First, research on walkability has overwhelmingly examined the developed nations, especially in the USA, Europe, Canada and Australia. Methodologies designed for land use planning in North America and Europe are not necessarily generalizable to developing countries, which should have different built environments and cultural contexts with the Western (Sallis et al., 2011). Alternative or revised approaches are seldomly developed for measuring the community walkability in developing countries. Second, it remains as controversy whether Walk Score is as a strong indicator of health disparities. Empirical findings are relatively lacking that evidence the linkage between walkability and health outcome indicators. Last, the social justice issue with respect to walkability is not adequately addressed in land use planning. The optimism about walkability should be significantly tempered if we cannot achieve a spatially equal profile of walkable communities. Understanding the relationships among community deprivation, walkability, and health outcomes will provide insights into the appropriate land use planning that supports public health promotion, and will test the assumed broader benefits of walkable environments.

China, the world's most populous country, is experiencing an epidemic of NCDs and obesity. It is reported that NCDs account for 86.6% of the total deaths and over 70% of the total disease burdens. In particular, cardiovascular disease, cancer, hypertension, and diabetes are the leading causes of deaths. Under such alarming circumstances, designing walkable communities to promote healthy living has become a timely issue (Day, 2016). The central government has launched a 'Healthy Community' program that outlines specific built environment characteristics in shaping public health. It is thus important to understand the links between community walkability and public health to help inform the extensive health promotion efforts. However, there is minimal research auditing community walkability and examining the corresponding role in public health. At the same time, cities in China expand at an accelerating pace to accommodate the booming urban population. It requires an estimated 40,000 km^2 new floor space, 5000 km^2 new road, and 170 new mass-transit systems (The State of China's Cities, 2010). Urban capacity is heavily outstripped to provide adequate fully equipped communities with transport convenience (Wan and Su, 2017). If walkable communities are not supplied or distributed equally, it should provide critical implications for health disparities and land use planning. Specifically, capturing the deprivation characteristics indicative of restricted community walkability will allow for more delicate contextualization of the health outcomes. Unfortunately, no report has been released regarding the social inequalities of community walkability in China.

The gap in the literature that this paper seeks to address is the walkability issue in China. Using a case of Shenzhen City, we aim to: (1) develop a revised approach based on Walk Score for measuring community walkability; (2) explore the association between community walkability and public health; (3) examine the social inequalities in walkability among the communities; and (4) provide some essential implications for land use planning. This study is unique because it captures the walkability in developing countries under a methodological framework compatible with the Western nations. Findings of this case should generate more generalized knowledge that enhances public health promotion within the land use planning context.

2. Literature review

2.1. Conceptualizations

The term of walkability originates from the walking ability of human being. Scholars have proposed several definitions of walkability. For example, Abley (2005) defined walkability as how friendly the built environment was to residential living, commuting, enjoying, shopping, or spending time within neighborhood area. Leslie et al. (2006) proposed the definition that "the extent to which characteristics of the built environment and land use may or may not be conductive to residents in the area walking for either leisure, exercise or recreation, to access services, or to travel to work". Gebel et al. (2009) set forth walkability as the extent to which the area was friendly for the pedestrians. Lwin and Murayama (2011) put forward walkability as how conducive the built environment is to walking. Implicitly, the idea of walkability is that people should become more active in walking in open urban environments (Moura et al., 2017). With respect to the factors affecting walkability, many individuals have associated walkability with different terms, which can be categorized into accessibility, connectivity, suitability, and perception. Accessibility has close relation with mixed land uses that shorten the distance between destinations and residences. Connectivity, as a consequence of grid patterns of street typology, represents the diversity and directness of the routes to destinations (Moura et al., 2017). Suitability denotes the physical factors are conductive to walking, including the presence of greenspaces, number of lanes, pedestrian width, transparency, air quality, crossing improvements, buffers to moving traffic, sun or shade in appropriate

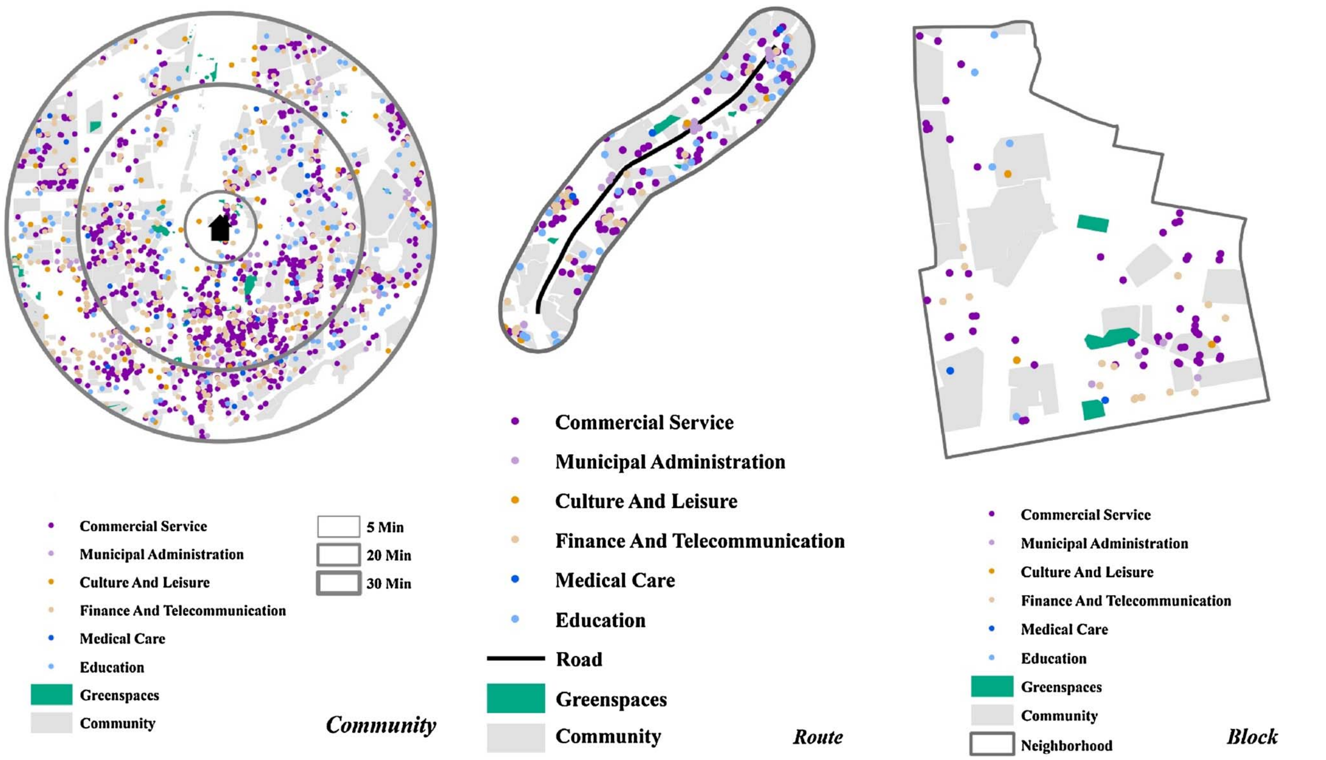

Fig. 1. Community (point), neighborhood (area) or street segment (route) level walkability.

seasons, nearby local destinations, and access to transport services (e.g., mass transit) (Dowling et al., 2008). Perception typically denotes the perceived safety regarding the heavy traffic or crime in population with certain sociodemographics (Gilderbloom et al., 2015). While these terms all have strong pull on walking behavior, literature generally reports that the accessibility and population sociodemographic characteristics are more synergistic determinants of walkability, and the suitability and connectivity are the subordinates to accessibility in the process of walkability assessment (Asadi-Shekari et al., 2013; Ewing and Cervero, 2010; Lo, 2009; Maghelal and Capp, 2011; Millington et al., 2009; Moura et al., 2017).

2.2. Measurement of walkability

Researchers in different fields (e.g., public health, geography, social science, urban planning, and transport engineering) have demonstrated various methodologies to measure walkability. Analysis is typically conduced at community (point), neighborhood (area) or street segment (line) level (Fig. 1). At the community and neighborhood level, scholars emphasize the accessibility and connectivity aspects of walkability and measure the convenience in accessing the daily amenities. At the segment level, researchers stress the suitability aspect of walkability and describe the pedestrian quality. The developed methods and tools include the indices, checklists, audit tools, in-field survey, geospatial inventories, cluster analysis, social questionnaires, and GIS (geographic information system) mapping (Azmi and Ahmad, 2015; Ewing and Handy, 2009; Hajna et al., 2013; Leslie et al., 2007; Maghelal and Capp, 2011). These different methods generate three major types of outcomes: (1) the number of elements that restrict or promote walking; (2) a value that indicates the low to high degree to which the analysis unit (community or street) is friendly for walking; and (3) clustered profiles of multidimensional characteristics of walkability for communities or street segments. For example, many individuals create walkability indices by combining variables that indicate net residential density, intersection density, land use mix, and retail floor area ratio and calculated corresponding values for measuring walkability (Eom and Cho, 2015; Frank et al., 2007; Greenwald and Boarnet, 2001; Learnihan et al., 2011; Owen et al., 2007; Sallis et al., 2009; Stockton et al., 2016). Others chose to develop walkability scale, framework, or scoring system that lists the terms indicative of walking suitability (Adlakha et al., 2016; Maiden et al., 2017; TRL, 2009; Zuniga-Teran et al., 2016). Several scholars classifies communities according to their walkability by incorporating a wide variety of attributes that are positively correlated to walkability (Adams et al., 2011; Cerin et al., 2007; McCormack et al., 2012; Moura et al., 2017).

Web-based applications are perhaps the most popular tools for measuring walkability. The Walk Score considers the distance to 13 amenities, maximizing the points within 5 min' walk and assigning a decay function for those 30 min away. The calculated scores are finally normalized into an interval from 0 to 100. Walkability (http://www.pitneybowes.com/us/data.html) considers a customizable set of physical indicators (e.g., point-of-interest accessibility, intersection complexity, street type, presence of water bodies and freeways, and population density) and integrates these indicators into three walk rating indices. Other factors (e.g., public transit, weather, and crime) are used to calculate the add-on scores. As a web app, the Walkonomics (http://www.walkonomics.com/) collects crowdsourcing and open source data to review and rate the street level walkability. Similarly, users are allowed to rate the street walkability on the website of RateMyStreet (http://www.ratemystreet.co.uk/), which uses Google Maps, crowdsourcing and a five star rating system (crossing, wayfinding, pedestrian width, trip hazards, safety, beauty, and disability infrastructure). The Walkability App (https://walkabilityasia.org/2012/10/03/walkability-mobile-app/#) allows users to rate the street walkability through nine items, including the disability infrastructure, motorist behavior, modal conflict, crossing points, safety, and others.

Previous studies have achieved great progress in walkability measurement. The developed tools can help land use planners and urban designers to improve the pedestrian quality and to establish walkable communities. However, one common problem with most methods and tools is the arbitrary selection of evaluation indicators and the unclear structuring of assessment criteria (Park et al., 2014). How to verify the

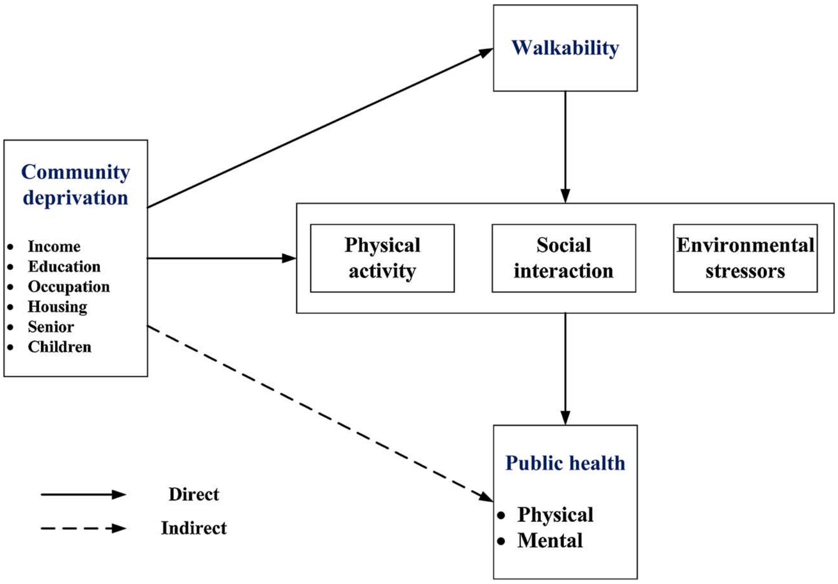

Fig. 2. Conceptual framework that hypothesizes the complex linkages among community deprivation, walkability and public health.

estimated outcomes is another key issue, as empirical cases are still limited to provide the answer. Some studies attempt to calibrate the outcomes through questionnaires, but significant gaps may exist between objective and subjective measures. A reliable and simple approach to verifying the walkability is to count the number of people engaging in active leisure activities within a community, route, block, or neighborhood. Nevertheless, it is very difficult to collect the samples in large areas. A further justification for walkability is needed to bridge the behavior, philosophy, and built environment. In addition, alternative tools should be established for developing countries due to the discrepancies in customs between Western and non-Western nations.

2.3. Walkability and health

Built environments have essential role in the etiology of health and health disparities (King, 2013). Prior studies have reported consistent associations between better health outcomes (e.g., reduced obesity, overweight, NCDs, and mental diseases) and living in walkable neighborhoods using various measures (Saelens and Handy, 2008; Sallis et al., 2009). With regard to the underlying mechanisms, a variety of pathways have been hypothesized and identified in existing publications. Some studies suggest that increased physical activity associated with a more walkable environment should mitigate obesity, NCDs and cancer (Adams et al., 2011; Ding et al., 2011; Steinmetz-Wood and Kestens, 2015). Accumulating evidence has claimed that more walkable attributes of built environments are predictive of active leisure activity, even when adjusting for subjective preferences (Frank and Engelke, 2005; Owen et al., 2007). Risk of NCDs can be substantially reduced by light-to-moderate activity. Hence, residents living in walkable environments should present better health outcomes. Other cases argue that more opportunities can be generated in walkable environments for inhabitants to meet, contact, and communicate. Such social activities can foster a sense of place attachment, safety, and satisfaction, which should plausibly benefit mental health considering the gained social support (Caspi et al., 2013; Jun and Hur, 2015; Sugiyama et al., 2008). Additionally, propensity to walk itself can be favored by positive neighborhood social interaction (King, 2013). Rather than continuing to underline primarily physical and social activities, recent literature asks the attention on a broad range of contextual mediators (Frank et al., 2005; Gilderbloom et al., 2015; Moura et al., 2017). For example, stressors such as crowd, pollution, and noise are also spatially correlated to urban form (Salomons and Pont, 2012; She et al., 2017; Yu and Kang, 2017), which may contravene or complement the effects of walkability on public health (Su et al., 2016a). As noted, earlier studies concentrate in North America and Europe, very few empirical studies to date have examined the linkage between neighborhood walkability and public health. Moreover, subjective walkability is typically used to capture the connection through questionnaire surveys. Objective walkability indices should be included to strengthen the evidence.

2.4. Walkability and deprivation

Neighborhood sociodemographic characteristics have close relations with health disparities. Researchers hold the view that build environments can reduce the social inequalities in health outcomes. A large body of literature has explored the varying walking behaviors associated with neighborhood sociodemographic characteristics. Several studies have investigated the relationship between perceived walkability and individual deprivation characteristics (Greenberg and Renne, 2005; Leslie et al., 2010; Pliakas et al., 2014; Wilson et al., 2004). Other cases have examined whether or not the health benefits of walkable built environments varies with socioeconomic groups (Kerr et al., 2007; Lovasi et al., 2009; Moniruzzaman and Páez, 2016; Owen et al., 2007; Sallis et al., 2009; Steinmetz-Wood and Kestens, 2015; Van Dyck et al., 2010). Due to different measures of walkable built environments, we cannot compare the mixed results reported in previous studies. Communities with large deprived population may be disproportionately affected by characteristics of less walkable neighborhood (Cutts et al., 2009). Unfortunately, limited studies have focused on the social inequalities in walkability itself. Kelly et al. (2007) found a negative association between neighborhood sidewalk conditions and percentage of African-Americans. On the contrary, Cutts et al. (2009) discovered that large African-American populations are more likely to live in walkable neighborhoods. We argue that understanding the association between community walkability and sociodemographics should inform land use planners to achieve built environments that reduce social inequalities and optimize public health and well-being.

3. Analysis framework

3.1. Conceptual framework

Based on the literature review, we propose a conceptual framework that hypothesizes the complex linkages among community deprivation, walkability and public health (Fig. 2). The conceptual framework provides an essential guidance for visualizing the interrelationships among

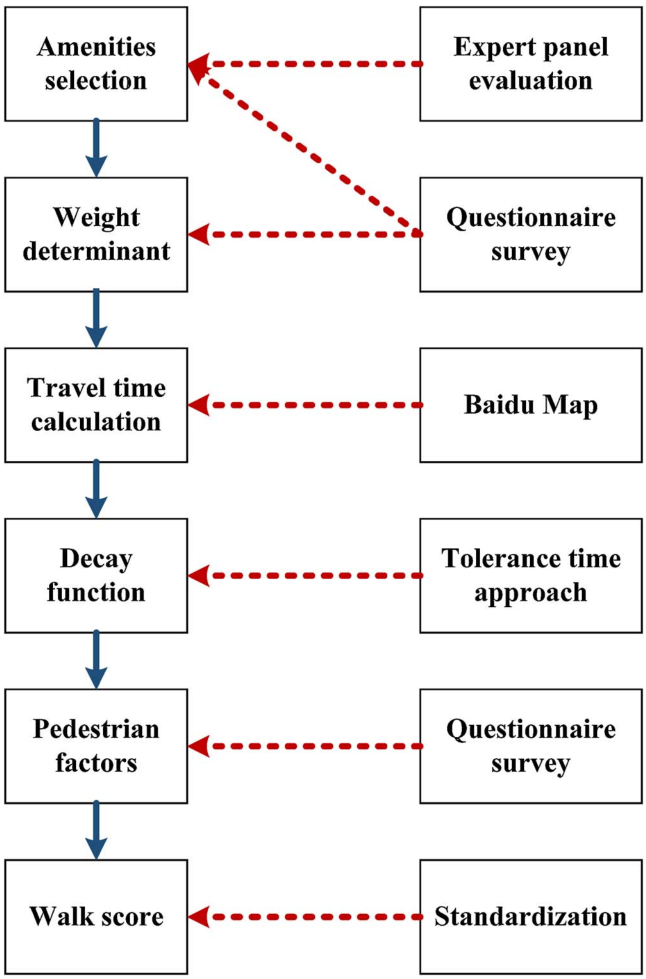

Fig. 3. Methodological framework for Chinese Walk Score development.

community deprivation, walkability and public health. Due to different built characteristics and social environments, communities present gradients in walkability. The existence of social inequalities is acknowledged on condition that lower walkability is found in socioeconomically disadvantaged communities. Deprivation and walkability both have potential influences on public health. Three casual pathways from community walkability to public health are included: (1) walkability motivates physical activity to promote health; (2) walkability fosters social interaction to enhance health; and (3) walkability regulates environmental stressors to influence health. Deprivation can be described by indicators of community socioeconomic disadvantage (e.g., income, education, occupation, housing type and population structure). Health can be assessed by either objective statistical data or subjective perceived status. Walkability can be typically measured using the Walk Score.

3.2. Methodological framework

Our study focuses on the community level walkability in China and thus attempts to demonstrate a revised approach based on Walk Score (Fig. 3). The Walk Score emphasizes the accessibility nature of walkability and has been widely used in the North America. For methodological details, reader can refer to the Walk Score (www.walkscore.com). In particular, we have to address three key issues for revising the Walk Score under a Chinese context: (1) amenities and weight; (2) decay function; and (3) incorporation of pedestrian characteristics. The original Walk Score considers 9 categories of amenities, including the restaurants, grocery stores, coffee shops, banks, parks, schools, libraries, and entertainment venues. Each of these amenities receives a weight according to their relative importance (frequency of utilization). High, moderate and low utilizing frequency is assigned as 3, 2, and 1; and the total weight sums to be 15. Some of amenities, for example the coffee shops and libraries, are not frequently visited in daily life of common Chinese residents. According to the Chinese Standard for Urban Community Design, the public facilities are divided into 8 principle categories and 50 items, namely education, medical care, culture and leisure, commercial services, finance and telecommunication, community service, municipal administration, and public administration. Expert panel evaluation are conducted to select the 8 amenities (50 items) for walkability assessment. One hundred and sixty experts participated in the process for indices selection through email feedbacks. These experts were from urban planning bureau, land authority, and urban scientists and all of them expressed strong willingness to participate in the walkability measurement. Each expert was given a manual that explained the whole procedure and all the amenities and items. In particular, expert judgment was guided by five criteria: measurability, discriminating ability, scientific validation, suitability, and scale appropriateness. Experts assigned a score to each item between 1 (very unfit) and 5 (very fit) by judging its relevance to the five criteria. The average score for each item was then calculated by assigning equal weight to all criteria and experts. Equal weight was assigned because no significant differences in scores were identified among the experts ($P = 0.11$) and the criteria ($P = 0.09$). When one or more experts assigned very low values to certain amenities, or pointed out severe unsuitability, these items were discarded. For each criterion, items with the top 5 scores were kept. Questionnaire survey was further employed to judge the selected items. We collected 1500 questionnaires (across occupation, age, education, and income) and asked the interviewees to select the items that were necessary in their daily life. We kept the items on condition that over 80% of the interviewees regarded

Table 1
Amenities (items) for walkability measurement in China.

Principle category	Sub-category	Third level	Weight
Commercial service	Shopping	Supermarket (1), Fresh market (1), Convenient store (0.5)	2.5
	Restaurant	Sit-in restaurant (1), fast food restaurant (0.5)	1.5
	Entertainment venues	Cinema (0.25), KTV (0.15), Barber shop (0.45), Gym (0.15)	1
Municipal administration	Public transport site	Metro entrance (2), bus stop (1)	3
Culture and leisure	Park and square		1
Finance and telecommunication	Finance	Bank (1), ATM (1)	2
	Post office		1
Medical care	Hospital	3A hospital (0.65), ordinary hospital and clinic (0.35)	1
	Pharmacy		1
Education	School		1

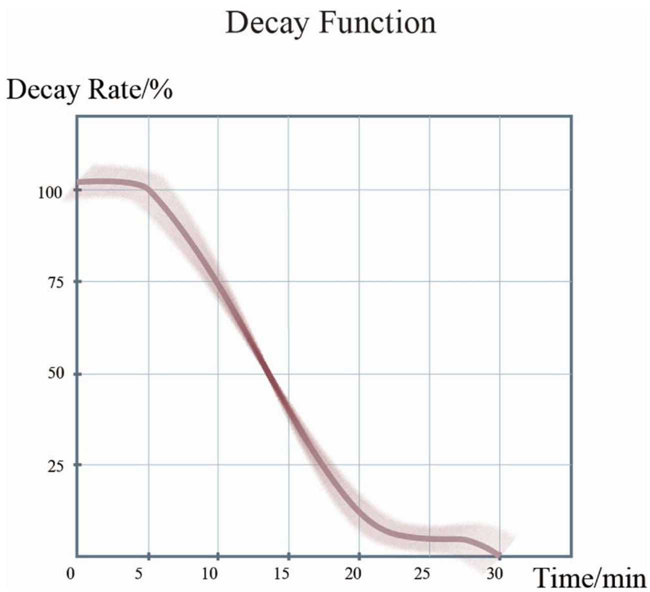

Fig. 4. Decay function.

to be necessary. Also, the interviewees also reported their utilization frequency (high, moderate and low) for each item and amenity, which is used for weight assignment. The final selected amenities and items as well as their weight are shown in Table 1.

For the decay function, we refer to the tolerance time approach demonstrated in Walk Score. Although the interviewees reported different tolerance time for different categories of amenities in our study, no significant differences based on the One-way ANOVA were identified among the amenities ($p > 0.05$). We thus calculate the average tolerance time and model the decay function (Fig. 4). Under the decay function, the Walk Score calculates the Euclidean distance from the residence to amenities. It may generate bias for ignoring the actual road network and transport information. To solve this problem, we refer to the Baidu Map (http://map.baidu.com) to calculate the travel time via walking from community to each amenity. It is argued that the Baidu Map can generate more accurate estimations, since the real-time transport conditions are considered (Su et al., 2017). Regarding the travel time estimated by the Baidu Map, readers can refer to Su et al. (2017) for details. After calculating the walkability based on the amenities and decay function, we further incorporate the pedestrian characteristics. We consider intersection density, block length, and slope as the decay adjusted factors (Table 2), since these three determinants are widely included in related literature. The final walk score are standardized into the interval between 0 and 100 (Table 3).

4. Data and processing

4.1. Study area

Shenzhen, occupying an area of 1953 km^2, is located in the Pearl River Delta (Fig. 5), extending geographically between 22°27′N − 22°52′N, and 113°46′E − 114°37′E. It houses over 10 million residential population. Since the 1980s, Shenzhen has experienced rapid socioeconomic development, transiting into a highly urbanized region from a traditional agricultural area. As one of China's megacities, the local government has sought to enhance city appearance and environment. Shenzhen has been entitled as "National Garden City", "International Garden City", and "Liveable City". At the same time, large quantities of migrant workers flowed into Shenzhen and sociosegregation has emerged as a challenging issue. Residential quality varies greatly across the communities within Shenzhen (Pi et al., 2016; Su et al., 2016b, 2017; Wan and Su, 2016; Weng et al., 2016; You, 2016). Thus, it is reasonable to examine the variations in community walkability and the associated social inequalities.

Table 2
Decay rate for the pedestrian characteristic factors.

Decay rate (%)	Intersection density (km^{-2})	Block length (m)	Slope (%)
0	> 200	< 100	< 0.2
1	150–200	100–120	0.2–1.0
2	120–150	120–150	1.0–5.0
3	80–120	150–180	5.0–10.0
4	50–80	180–200	10.0–20.0
5	< 50	> 200	> 20

Slope refers to the ratio between vertical height and horizontal length for a POI.

Table 3
Walk score grade and representation.

Walk score	Indication
0–24	Not suitable for walking Residents nearly cannot reach all of the daily destinations via walking.
25–49	Lowly suitable for walking Residents can reach a few of the daily destinations via walking.
50–69	Moderately suitable for walking Residents can reach some of the daily destinations via walking.
70–89	Very suitable for walking Residents can reach majority of the daily destinations via walking.
90–100	Highly suitable for walking Residents can reach all the daily destinations via walking.

4.2. Data sources and processing

Point vector data of communities (8117 in total) and the six categories of amenities, line vector data of road networks, and polygon vector data of block are provided by Shenzhen's Geographic Information Center. For the walking time from each community to the amenities within tolerance time, a crawling tool is developed to harvest the information. Then, the walk score is calculated and standardized by following the proposed methodology and using a GIS. In order to explore the spatial patterns of walkability, we further visualize the walk score by employing the Global Moran's I and the Local Indicators of Spatial Association analysis (LISA). LISA identifies the spatial outliers and clusters across space (Anselin, 1995) and Moran's I describes the spatial autocorrelation (Moran, 1948). Value of Global Moran's I minimizes -1 (chessboard distribution) and maximizes $+1$ (absolute positive spatial autocorrelation). The value of 0 indicates a randomly distributed pattern (Anselin, 1995). LISA is categorized into four types, namely high–high clusters, high-low outliers, low–low clusters, and low-high outliers (Anselin et al., 2006). Moran's I and LISA are calculated by using a nearest neighbor distance matrix.

Seven variables are selected to describe the community level sociodemographic characteristics (Table 4). These five variables are chosen because of (1) data availability; (2) low redundancy; and (3) comparability with previous studies of Shenzhen (Pi et al., 2016; Su et al., 2016a, 2017; Wan and Su, 2016; Weng et al., 2016; You, 2016). Data for 5 health indicators (cardiopathy, chronic hepatitis, chronic pneumonia, hypertension, and liver cancer) in 2011 are provided by the Shenzhen Health Information Center. The following equation (Eq. (1)) is used to calculate the incidence rate (p) of each disease for the 8117 communities (Coggon et al., 1997; Su et al., 2016b; Weng et al., 2016). General descriptive statistics of the five health outcomes are shown in Table 5.

$$p_{ij} = \frac{n_{ij}}{N_j} \quad (1)$$

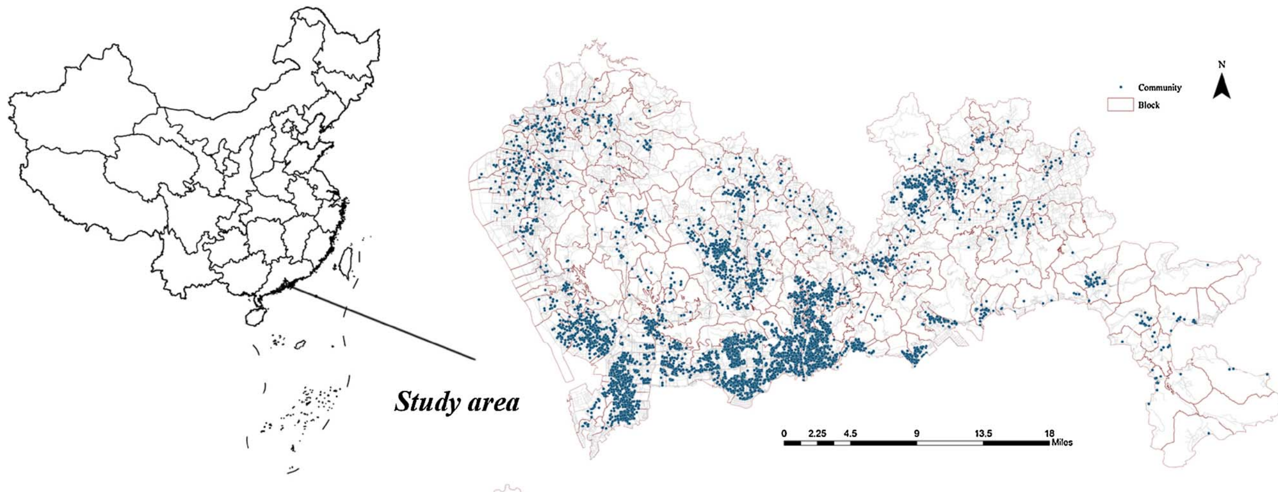

Fig. 5. Location of Shenzhen (China) as well as the community and block division within it.

where p_{ij} is the incidence rate of disease i for community j; n_{ij} is the total cases of disease i in community j in 2011; N_j is the total population in community j.

4.3. Spatial regression

Considering the spatial autocorrelation of community walkability, spatial regression is used to explore the associations between community sociodemographics and walkability as well as those between community walkability and health outcomes. More specifically, spatial regression typically incorporates two categories of autocorrelation (Anselin, 1988), namely spatial lag (Eq. (2)) or error (Eq. (3)). Before regression, we normalize and standardize all the variables. In particular, the spatial autocorrelation form (error or lag) is specified in reference to the robust Lagrange multiplier. The spatial matrix is constructed by using the nearest neighbor distance matrix.

$$Y = \alpha + \beta X + \lambda W_Y + e \tag{2}$$

$$Y = \alpha + \beta X + e(e = \lambda W_e + u) \tag{3}$$

where X and Y are the exploratory and dependent variable; W_Y and W_e are the spatial matrix for dependent variable and error term; λ is the spatial autoregressive coefficient; e is the error term; β is the coefficient for exploratory variable; α and u are the scalar variables.

4.4. Path analysis

Path analysis based on the robust maximum likelihood estimator is utilized to identify the complex linkages among community deprivation, walkability and health outcomes. A series of regression equations are tested by the path analysis, in which the variables are treated as the predicators, mediators, and outcomes. These variables are further apportioned into direct, indirect and total components according to their marginal effect (Hoyle, 1995; Stenberg et al., 2013). We first test all the possible paths under the conceptual framework (Fig. 1) and then remove the insignificant paths ($p > 0.05$). For the possible mediating factors between walkability and public health, we only consider air pollution ($PM_{2.5}$) and exclude physical activity and social interaction given data availability. A land use regression is established for Shenzhen based on the official annual average $PM_{2.5}$ monitoring data (Su et al., 2016a). We sum the average $PM_{2.5}$ for the 8117 communities, respectively. The Mplus 5.2 is used to perform the path analysis.

Table 4
Selected community sociodemographic variables (N = 8117).

Variables	Explanation	Max	Min	SD	Mean
Living alone	Proportion of people living alone	1.00	0.00	0.15	0.10
No house property	Proportion of people without house property	1.00	0.00	0.19	0.09
Unemployment	Proportion of unemployed people	1.00	0.00	0.15	0.08
Less educated	Proportion of people with degree lower than middle school	1.00	0.00	0.10	0.04
Blue-collars	Proportion of people aged 60 and above	1.00	0.00	0.08	0.04
Elder	Proportion of blue-collar workers	1.00	0.00	0.20	0.12
Children	Proportion of people aged 12 and below	0.12	0.01	0.05	0.02

5. Results and discussion

5.1. Patterns of community walkability

Spatial patterns of the walk score are shown in Fig. 6. We observe the geography (Fig. 6a) that higher walk scores (> 70) concentrate in the central blocks and majority of the communities present quite lower walk scores (0–24). It indicates the great variations in walkability among the 8117 communities within Shenzhen. As shown in Fig. 6b, the Moran's I reaches 0.36 ($p < 0.01$), suggesting that the community walkability should be autocorrelated. More specifically, communities should present similar walkability with their neighboring communities. Compatible with Fig. 6a, the high–high clusters are located in the central blocks, and the low–low clusters emerge in the blocks within the outskirts. These results imply that great spatial inequalities should exist in walkability among the communities within Shenzhen.

5.2. Community walkability and health

Table 6 demonstrates the associations between community

Table 5
Descriptive statistics of health outcome indicators (N = 8117).

	Min	Max	Mean	Std	Unit
Cardiopathy	14.0	452.0	122.7	10.7	1/100000
Chronic hepatitis	3.1	67.0	16.3	5.5	1/100000
Chronic pneumonia	44.2	496.4	170.6	20.9	1/100000
Hypertension	58.4	865.3	199.7	17.9	1/100000
Liver cancer	1.4	37.6	10.3	8.8	1/100000

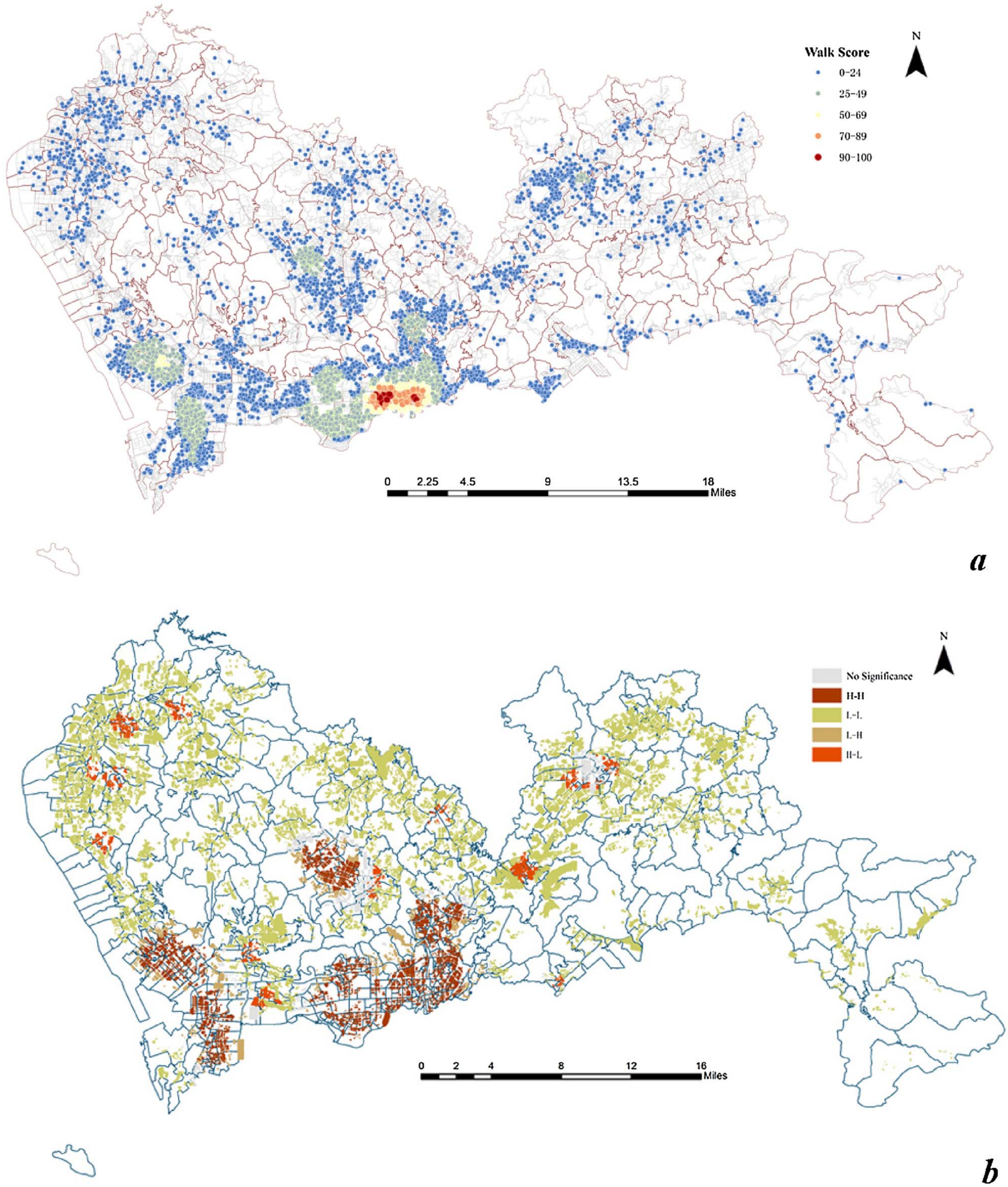

Fig. 6. Spatial pattern of walk score (a) as well as clusters and outliers (b) H-H (high-high), L-L (low-low), L-H (low-high), and H-L (high-low).

walkability and health outcomes. It can be seen that community walk score presents negative association with cardiopathy, hypertension, and liver cancer but have no significant relationship with chronic hepatitis and chronic pneumonia. It suggests that lower incidence of heart diseases, hypertension, and liver cancer would be observed in more walkable communities. Our findings accord with prior studies that residents in more walkable neighborhoods should have better health outcomes (Ding and Gebel, 2012; Dunton et al., 2009; Goodwin et al., 2013; Hoehner et al., 2011; King, 2015; Saelens and Handy, 2008; Sallis et al., 2009). It also supports the argument that built environment should have a substantial role in shaping health (King, 2013; WHO, 2010). We can infer that the hypothesis (Fig. 2) on the linkage between community walkability and health outcomes should stand not only for the Western nations but also for the developing countries like China.

5.3. Community walkability and sociodemographics

Table 7 shows the relationships between community walkability

Table 6
Relationships between community walkability and health outcomes identified by spatial regression (N = 8117).

Health outcomes (Y)	Regression	R^2
Cardiopathy	$Y^a = -0.12 \times X + 1.29 \times W_Y + 0.21$	0.26**
Chronic hepatitis	NS[b]	
Chronic pneumonia	NS[b]	
Hypertension	$Y^a = -0.09 \times X + 1.45 \times W_Y + 1.08$	0.14**
Liver cancer	$Y^c = -0.03 \times X + 1.58$ (Lambda = 2.45)	0.05**

** $p < 0.01$.
[a] Spatial lag regression: WY is the spatial weight for Y.
[b] NS: no significance.
[c] Spatial error regression.

and sociodemographics. Except the Living alone%, all the sociodemographic variables are significantly correlated with walk score. In particular, walk score is negatively correlated to No house property%, Unemployment%, Less educated%, Blue-collars%, and Children%, but negatively associated with Elder%. It indicates that children concentrated and socioeconomically disadvantaged communities exhibit lower walkability. On the contrary, the elder concentrated communities are characterized by higher walkability. These results evidence that significant social inequalities in walkability should exist among the communities in Shenzhen. The deprived population typically settle in communities with lower apartment rent or house price. These communities are thus expected to see higher percentage of unemployed or less-educated people. However, these communities generally have quite lower density of public densities and limited transportation convenience. This accounts for the low walkability of the socioeconomically disadvantaged districts. The young couples usually cannot afford the high housing price in the central blocks and tend to reside in the outskirts. Supporting facility construction for these communities are relatively lagged behind housing development. It leads to the lower walkability in the children concentrated communities. Elder population due to mobility constrain tends to reside close to public transport where a diversity of public facilities concentrate. Local seniors generally concentrate in the communities of the old central place, where public facilities are dense and streets are connective. It contributes to the high walkability in the elder concentrated communities.

5.4. Complex linkages among community deprivation, walkability, and public health

Table 8 summarizes the significant paths among community

Table 7
Relationships between community walkability and sociodemographics identified by spatial regression (N = 8117).

Sociodemographic variables (X)	Regression equation	R^2
Living alone	NS[a]	
No house property	$Y^b = -0.35 \times X + 0.87 \times W_Y + 1.56$	0.07**
Unemployment	$Y^b = -0.67 \times X + 1.23 \times W_Y + 0.33$	0.19**
Less educated	$Y^b = -0.35 \times X + 0.21 \times W_Y + 1.24$	0.23**
Blue-collars	$Y^b = -0.79 \times X + 1.05 \times W_Y + 0.41$	0.15**
Elder	$Y^c = 0.14 \times X + 0.35$ (Lambda = 1.51)	0.13**
Children	$Y^c = -0.05 \times X + 1.02$ (Lambda = 0.67)	0.09**

** $p < 0.01$.
[a] NS: no significance.
[b] Spatial lag regression: WY is the spatial weight for Y.
[c] Spatial error regression.

Table 8
Causal paths among community deprivation, walkability, and public health.[a]

Health outcomes	Identified path
Cardiopathy	No house property% → (−) walkability → (−) Cardiopathy Less educated% → (−) walkability → (−) $PM_{2.5}$ → (+) Cardiopathy Unemployment% → (+) $PM_{2.5}$ → (+) Cardiopathy Blue-collars% → (−) walkability → (−) Cardiopathy
Hypertension	Less educated% → (−) walkability → (−) $PM_{2.5}$ → (+) Hypertension Unemployment% → (−) walkability → (−) Hypertension Blue-collars% → (+) $PM_{2.5}$ → (+) Hypertension
Liver cancer	NS[b]
Chronic hepatitis	NS[b]
Chronic pneumonia	NS[b]

[a] (−) represents negative correlation and (+) denotes positive association.
[b] NS: no significant paths are identified.

deprivation, walkability, and public health. No significant paths are found for the other three diseases (chronic hepatitis, chronic pneumonia, and liver cancer). For cadiopathy and hypertension, three categories of significant paths are identified. First, residents in deprived community have worse health outcomes due to lower walkability. Second, poorer health outcomes occur in deprived communities as a result of higher $PM_{2.5}$ exposure. Third, less walkable communities are exposed to greater $PM_{2.5}$ concentration and deprived communities are generally characterized by lower walkability and consequently have worse health outcomes. These results demonstrate that the linkages among community deprivation, walkability, and public health should be very complex. Our findings support the argument that a broad range of contextual mediators should be examined besides the physical activity and social interaction with regard to the association between walkability and public health (Frank et al., 2005; Gilderbloom et al., 2015; Moura et al., 2017). These discoveries also evidence that walkability itself acts as the mediator between community deprivation and public health.

6. Implications for land use planning

Traditionally, local health authorities are responsible for identifying the health risk factors and addressing health disparities. They are thus expected to develop, adopt and implement plans and policies that facilitate the healthy living benchmarks (e.g, leisure activity) to be met. However, critical practice gaps exist since knowledge of community design and built environment regulation appears low. Researchers point that health authorities, compared with other public sector officials, report greater barriers to consider built environments and lower involvement in developing corresponding policies related to urban design and land use (Maiden et al., 2017; Su et al., 2016a). Land use planning controls the nature and sustainable changes of urban design and built environment (Rossen and Pollack, 2012). Hence, formulating regulations that gear towards active living through land use planning should be a golden opportunity for addressing health disparities and promoting public health (Gordon-Larsen et al., 2006; Maiden et al., 2017; Su et al., 2016a). Nevertheless, land use planners in developing countries like China are faced with the dilemma that practical tools are absent for guiding the health implications of land use planning (Su et al., 2016a).

This paper creates a Walk Score tool that measures the community walkability pertaining to healthy living promotion under Chinese context. This tool not only brings a standardized measurement of walkability in the field of land use planning, but also paves the way for including health concerns in community design across various jurisdictions. Beyond the friendliness for the pedestrians, the score indicates the health disparities associated with the built environments.

For example, a score of 24 indicates a high health risk associated with lower walking suitability. As a result, land use planners can use this tool to identify the isolated communities with poor walkability as the priorities for further improvement in land use regulations. Additionally, the practitioners can document the changes of community walkability over time based on the numeric scores. It gauges how the current land use plans match with an official benchmark, and facilitates a comparison among different land use regulations. In response, planners can guarantee a not too overwhelming way for updating the land use regulations. The developed Walk Score tool also has far-reaching implications for addressing social inequalities in land use planning. We find that the less walkable communities are those concentrated by deprivation population and are also exposed to greater air pollution. It demonstrates that the needs of deprived communities and households are exclusive in many ways realistically within existing land use planning schemes in China. Currently, China's land use planning places overwhelming emphasis on the overall average level over equally distribution of public resources (Li and Liu, 2016; You, 2016). It results in the alienation and disempowerment of the deprived groups that they intend to empower and include. We therefore argue that social inequalities in walkability should capture the attention of land use planners.

In order to address the social inequalities in walkability for public health promotion, three areas should be given priorities in future land use planning. First, urban form-based zoning schemes can be proposed to replace the traditional Euclidian distance based approach. It can generate a more mixed land use framework moving away from individual land use dominance pattern. As a result, communities would become accessible to increasing number and diversity of destinations and amenities within tolerance walking time. Second, economic inputs for streetscape improvements are needed especially for the deprived neighborhoods. Land use planners should recognize the necessity of spatially equal walkability as well as the health benefits of improved built environments. Typical approaches for improving streetscapes include providing greenbelts and sidewalks, constructing benches and shelters, balancing street with pedestrian widths, installing crosswalks, and exhibiting art. Third, existing inequalities may be exacerbated as a consequence of simply increasing investment in an area. Thus, affordable and low-renting housing policies should be formulated, since deprived population may face increasing economic burden after streetscape improvement. These three solutions, when conducted in parallel, have great potential to achieve socially equal walkable communities in Shenzhen.

7. Conclusions

This paper attempts to address the walkability issue in China. We develop a revised Walk Score tool for measuring community walkability. Under the original Walk Score methodological framework, (1) 6 principle amenities (19 items) and their weight (utilization frequency) are first selected by expert panel evaluation and questionnaire survey; (2) a tolerance time approach is then employed to determine the decay function, and the walking travel time from community to each amenity is calculated by using the Baidu Map; and (3) three pedestrian characteristic factors (intersection density, block length, and slope) are considered to adjust the score. We apply the proposed methodology to the case of Shenzhen and find great variations in walkability among the 8117 communities within it. The high–high clusters are located in the central blocks, while the low–low clusters emerge in the blocks outside the economic special zone. Using spatial regression, we obtain significant negative associations between community walkability and three health indicators (cardiopathy, hypertension, and liver cancer). It suggests that better health outcomes would be observed in more walkable communities. We further discover that children concentrated and socioeconomically disadvantaged communities exhibit lower walkability. It evidences that significant social inequalities in walkability should exist among the communities in Shenzhen. Path analysis identifies complex linkages among community deprivation, walkability, and public health. More specifically, three categories of significant paths are identified: (1) residents in deprived community have worse health outcomes due to lower walkability; (2) poorer health outcomes occur in deprived communities as a result of higher $PM_{2.5}$ exposure; and (3) less walkable communities are exposed to greater $PM_{2.5}$ concentration and deprived communities are generally characterized by lower walkability and consequently have worse health outcomes.

The developed Walk Score tool not only brings a standardized measurement of walkability in the field of land use planning, but also paves the way for including health concerns in community design across various jurisdictions. It is very difficult and nearly impossible to verify the work score. However, it is believed that longitudinal and horizontal comparisons of the walk score should largely reduce the subjectivity and uncertainty. The street Monitoring System or volunteered pedometers can be used to solve this problem, since we can count the frequency of residents walking around the neighborhood. We argue that social inequalities in walkability should attract the attention of land use planners. In order to address this pressing issue, three areas should be given priorities in future land use planning: (1) adopting urban form-based zoning schemes; (2) economic inputs for streetscape improvements; and (3) formulating affordable and low-renting housing policies. Following studies should develop more advanced methods to calculate the walk score. In particular, the present walk score can in revised in three points: (1) the decay function can be developed for different amenities, towards which residents may show varying tolerance; (2) the categories of amenities and their relative weight can be adjusted according to region-specific characteristics; and (3) more pedestrian and demographic characteristics can be incorporated into consideration.

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Appendix A

Land Use Plan	Country	Essential points
New Urbanism	United States	Creating walkable neighborhoods to promote environmentally friendly habitats.
Transportation for America	United States	Completing the transportation network to sustain productive and healthy lives.
Smart Growth America	United States	Building neighborhoods, towns, and cities that are safe for people walking.
National Complete Streets Coalition	United States	Everyone has convenient access to public places and destinations via walking.

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