Journal of Transport & Health 13 (2019) 259–273

Contents lists available at ScienceDirect

Journal of Transport & Health

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

The 15-minute walkable neighborhoods: Measurement, social inequalities and implications for building healthy communities in urban China

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ARTICLE INFO

Keywords:
Walkability
Walk score
15-Min walkable neighborhoods
Social equality
Healthy communities
China

ABSTRACT

A sufficient number of studies have highlighted that walkable neighborhoods can help to reduce the risk of obesity and noncommunicable diseases (NCDs). The Chinese government advocates the 15-minute (15-min) walkable neighborhoods to provide citizens with 15-min walkable access to basic public services, and ultimately to improve walking behavior and overall health. Following the Walk Score metric, this paper proposes a modified method for measuring 15-min walkable neighborhoods and applies it to Shanghai, China. Based on amenity access, the assessment considers walking demands of different pedestrian groups (i.e., the entire population, children, adults, and seniors), the amenity attributes (scale and category), and the real traffic conditions. Spatial regression is further performed to determine whether significant associations exist between community socioeconomic status and 15-min walkable neighborhoods score. Results show clear variations in 15-min walkable neighborhoods score for different pedestrian groups. Regarding the overall 15-min walkable neighborhoods, highly walkable communities are primarily concentrated in the central areas; and that poorly walkable communities are dispersed in rural areas. Senior-concentrated and adult-concentrated communities are more likely to present higher walkability, while children-concentrated communities exhibit lower walkability. Moreover, communities with inferior walkability are characterized by a high proportion of floating population (nonresidents). This research provides future studies with references for evaluating 15-min walkable neighborhoods. Social inequalities in 15-min walkable neighborhoods should be emphasized, and interventions in planning implementation for building healthy communities in China should be targeted.

1. Introduction

Improving physical activity levels, decreasing the number of overweight and obese people, and reducing rates of noncommunicable diseases (NCDs) have become major public health initiatives in many countries (World Health Organization, 2015). Walking, as an easily available and healthful form of physical activity (Pliakas et al., 2014), can leads to weight control and prevention of hypertension, heart disease, and diabetes (Azmi and Ahmad, 2015). National policies, strategies and plans of action have

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https://doi.org/10.1016/j.jth.2019.05.005
Received 15 October 2018; Received in revised form 6 May 2019; Accepted 13 May 2019
Available online 28 May 2019
2214-1405/

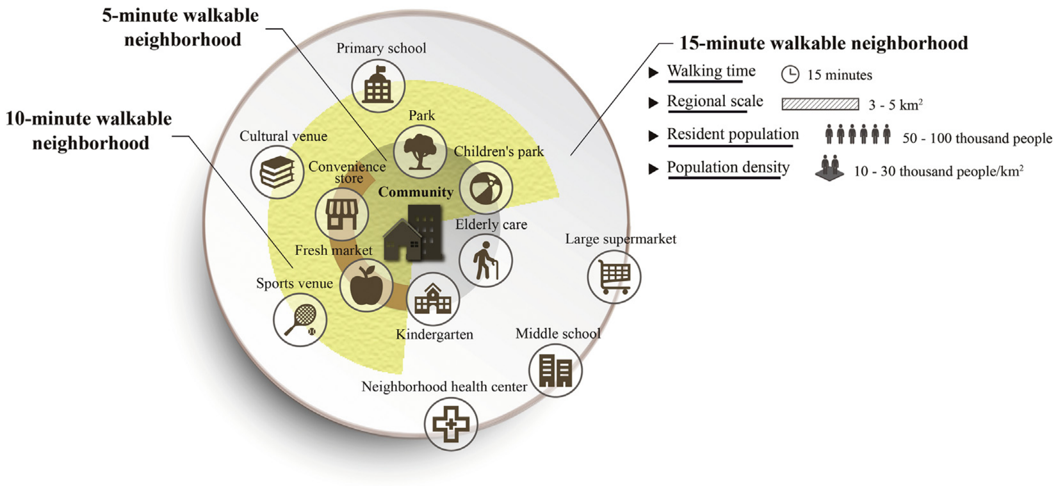

Fig. 1. Schematic diagram of 15-min walkable neighborhoods.

been proposed by several governments and organizations across the globe to prevent chronic diseases, obesity and overweight through designing walkable built environment (World Health Organization, 2015; United Nations, 2015). Examples include the New Urbanism (http://www.newurbanism.org), the Walkable London (https://www.walkablelondon.co.uk), the Smart Growth America (https://smartgrowthamerica.org), the Leadership in Energy and Environmental Design for Neighborhood Development (LEED-ND) (https://www.usgbc.org/guide/nd), the Transportation for America (http://t4america.org) and China's 15-min Walkable Neighborhoods (Fig. 1).

Walkability is defined as the extent to which the built environment has a positive effect on walking (Moura et al., 2017). Scholars have broadly accepted that better neighborhood walkability should improve physical activity (including leisure-time physical activity), active transportation, and mental health (Rundle et al., 2016; Todd et al., 2016; Zuniga-Teran et al., 2016), and there is sufficient evidence on the relationship among the built environment, walkability, and health outcomes (King et al., 2011; Lovasi et al., 2011; Su et al., 2017a; Fan et al., 2018). Researchers have proposed various models and indicators to assess walkability. Approaches, including subjective perception and objective dimensions (Boakye-Dankwa et al., 2019; Leslie et al., 2007; Pliakas et al., 2014), have been reported in previous studies. Social questionnaires, individual surveys or interviews, accelerometers, and GIS-based approaches are some of the most popular assessment methodologies (King et al., 2011; Knight et al., 2018; Moura et al., 2017).

Walk Score, a destination-based metric in particular, has been validated and highly recommended for its effectiveness in measuring neighborhood walkability in different regions (Carr et al., 2010; Duncan, 2013). High correlation has been found between Walk Score and other objective assessments that considering intersection density, residential density, access to public transit, and sidewalk availability (Koohsari et al., 2018). However, it is generally accepted that a "one-size-fits-all" measurement does not exist for walkability, making it inappropriate to apply same methods to completely disparate urban environments (Guo and Loo, 2013; Lee and Talen, 2014; Manaugh and El-Geneidy, 2011). Accordingly, three limitations should be further addressed. First, studies on neighborhood walkability are lacking in developing countries, where residential living modes are quite different from western development. Second, although recent Walk Score procedure has replaced Euclidean distance with network distance (Koohsari et al., 2018; Nykiforuk et al., 2016), ignoring actual traffic situation may lead to measurement errors. The raw score usually needs to be adjusted by block length and intersection density (Koohsari et al., 2018). Finally, the social equality issue in walkability is partly underemphasized in related studies. In fact, social inequalities may exist among different socioeconomic groups (e.g., children, seniors, migrant workers, and less educated) (Wan and Su, 2017; Weng et al., 2017). However, most of the current studies focus on the entire population or a specific group (e.g., children, adults, or seniors), so comparative studies of neighborhood walkability among different pedestrian groups are relatively lacking.

This paper aims to address the above limitations in walkability measurement within the context of China's 15-min Walkable Neighborhoods. It is important to explore an appropriate evaluation method in China where central government has proposed to construct sustainable and livable cities. The specific purposes are to: (1) propose a method for measuring 15-min walkable neighborhoods by modifying the Walk Score metric; (2) determine the social inequalities inherent in building 15-min walkable neighborhoods; and (3) provide insightful suggestions for building healthy communities in urban China.

2. Literature review

2.1. Measurement of walkability

Approaches and tools for measuring walkability mainly involve checklists, social questionnaires, indices, individual surveys, audit systems, inventories, spatial analysis and geographic information systems (GIS) (Ewing and Handy, 2009; Leslie et al., 2007; Todd et al., 2016). The tools can be broadly divided into two different categories: (1) elements that affect walking and (2) a score used to rate the area from poorly to highly walkable. Furthermore, analyses are implemented at different scales, from the census block group to the neighborhood area, street segment, and community point (Bereitschaft, 2017; Moniruzzaman and Paez, 2016; Moura et al., 2017; Su et al., 2019). To construct a composite walkability index, numerous researchers have classified environment-related features to obtain assessment indicators, and the majority of studies adopt several of the same critical elements. One of the most widespread walkability indices was developed by Frank et al. (2005), and included the following factors: land use mix, street connectivity, and net residential density, and was extended later by adding another factor, the retail floor area ratio (Frank et al., 2006, 2010). Based on density, diversity and design, supplementary indicators, including distance to transit and destination accessibility, have been put forward for building the 5D's model (Ewing et al., 2013). Although these elements are either conducive or detrimental to walking, related studies demonstrate that features, such as land use mix and demographic characteristics, contribute more to walkability measurement because traditional factors, such as connectivity, are dependent on accessibility in terms of walking behavior promotion (Moura et al., 2017; Ewing and Cervero, 2010). Moreover, studies conducted in different urban contexts have shown great disparities in the relationship between built environment characteristics and walking (Alfonzo et al., 2014; Azmi and Ahmad, 2015; Day, 2016; Lu et al., 2017). Data of built environment indices usually vary by regions, to an extent, restricting comparability (Hirsch et al., 2013). It is generally agreed that the most prevalent instruments for measuring walkability ought to be web-based applications. Walk Score (https://www.walkscore.com) is calculated by combining distances weighted by distance decay functions and amenity categories. Walkshed provides users with a heat map showing neighborhood walkability (http://www.walkshed.org/nyc). Walkonomics (http://www.walkonomics.com) evaluates the walkability of every street segment. Additionally, some developed countries have proposed systematic tools for measuring walkability, such as the Pedestrian Environment Review System (PERS), the Neighborhood Environment Walkability Scale (NEWS), the Pedestrian Environmental Quality Index (PEQI), and the Community Street Review (CSR). These tools can help planners to identify deficiencies and to build walkable communities; however, being sensitive to evaluation indicators, which still needs to be optimized (Park et al., 2014; Su et al., 2017a).

2.2. Social inequalities in walkability

Existing studies have gradually placed emphasis on the social inequalities in walkable urban neighborhoods, and a growing number of studies explore the relationship between neighborhood walkability and social disadvantage (e.g., low-income people, the less educated, and minorities) from the spatial and statistical perspective (Bereitschaft, 2017; Riggs, 2016). Knight et al. (2018) found that non-walkable neighborhoods in the city of Buffalo, New York, are predominantly home to black and low-income residents, where the housing vacancy rates are quite high and housing prices are very low. Riggs (2016) also noticed that blacks are more likely to concentrate in neighborhoods with low walkability in the San Francisco Bay area. Block groups with inferior walkability and a high proportion of disadvantaged groups are generally characterized by large number of less educated, non-white (mainly black) residents, the impoverished, and low-skill service workers (Bereitschaft, 2017). Regarding specific facilities, researchers have proven that it is difficult for disadvantaged groups to get equal opportunities to utilize service facilities or even basic commercial, educational, recreational or medical services and resources. Examples include parks and green spaces (Xu et al., 2017), large grocery stores and supermarkets (the deficiency of which is defined as a “food desert” – an area with limited access to affordable and healthy foods) (Hilmers et al., 2012; Su et al., 2017b), public transport (McKenzie, 2013; Welch, 2013), medical care amenities (Hawthorne and Kwan, 2012), and various recreational facilities (Moore et al., 2008). However, it is notable that these studies reveal that whether or not social inequalities exist in neighborhood walkability varies with different urban contexts. For instance, Riggs (2016) found a negative association between walkability and minorities, but no significant relationship was testified by Duncan et al. (2008). Macdonald et al. (2016) demonstrated that the least deprived areas show the lowest walkability in Urban Scotland, while the poorest areas exhibit lower walkability in Glasgow City. Current studies should pay close attention to the characteristics of different populations, for instance, seniors and children may have diverse preferences and needs regarding amenity accessibility (La Rosa et al., 2018). Also, rural-urban migrants are confronted with social and geographic segregation in residence and public services (Weng et al., 2017; Xu et al., 2017; You, 2016). Unless different socioeconomic characteristics are considered, no tool for evaluating walkability can assist planners in taking targeted measures to build more equitable and walkable cities. With such issues in mind, examining whether varying socioeconomic groups enjoy equal access to desirable facilities in neighborhoods is greatly needed.

3. Study area and data

Located in the Yangtze River Delta, Shanghai is the most rapidly urbanizing and developed megacity in China. It borders the Jiangsu province and Zhejiang province and is adjacent to the East China Sea (Fig. 2). It has undergone significant socioeconomic transformations over the past forty years (Li et al., 2019b). However, increasing incidence of noncommunicable diseases has been observed during the past decades (Bloom et al., 2018). In response, the local government has advocated the “15-min walkable neighborhoods”, aiming at providing basic public services such as education, medical care, elderly care, and commercial services within 15-min walking distance for each community. In this way, the overall walking behavior would be promoted, which in turn leads to public service equalization, increased motivations to be healthy, and improvements in the quality of urban life. The Shanghai planning guidance for 15-min walkable neighborhoods was published in August 2016, thus we used dataset in 2016 to evaluate current walkability and expected to support policy implementation.

Digital geographic data, including communities, road networks, and amenity Points of Interest (POIs) with precise geographical coordinate (CGCS 2000), are acquired from local government. Demographic data, which are collected from the sixth national

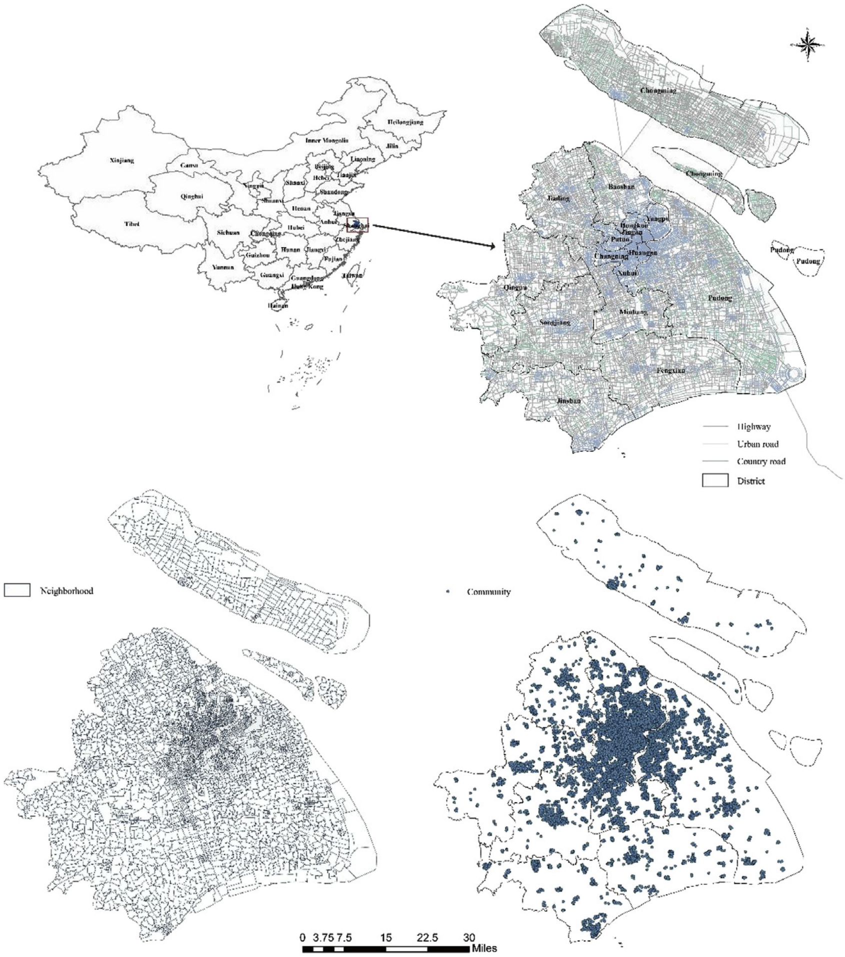

Fig. 2. Location of Shanghai (China) as well as the neighborhood and community divisions within it.

population census (National Bureau of Statistics of China, 2010), include eight socioeconomic status variables. More specifically, % Children is proportion of people aged 12 years old and below. % Adults is proportion of people aged 18–59 years old. % Seniors is proportion of people aged 60 years old and above. % Females is proportion of females. % Minorities is proportion of minorities. % Separation of registered and actual residence is proportion of residents who do not live in registered location. % Non-registered is proportion of floating population (nonresidents). % Agricultural registered is proportion of rural residents. The descriptive statistical summary of the socioeconomic status variables is shown in Table 1.

Table 1
Descriptive statistics of residential sociodemographic variables (N = 13063).

Variable	Min	Max	Mean	SD
% Children	0	100	52.05	10.71
% Adults	0	75	37.87	7.27
% Seniors	0	98.78	10.08	5.75
% Females	0	100	49.19	6.76
% Minorities	0	40.48	1.07	1.41
% Separation of registered and actual residence	0	76.09	7.45	11.43
% Non-registered	0	100	37.1	22
% Agricultural registered	46.59	100	97.95	2.32

Abbreviations: % Children is proportion of people aged 12 years old and below; % Adults is proportion of people aged 18–59 years old; % Seniors is proportion of people aged 60 years old and above; % Females is proportion of females; % Minorities is proportion of minorities; % Separation of registered and actual residence is proportion of residents who do not live in registered location; % Non-registered is proportion of floating population (nonresidents); % Agricultural registered is proportion of rural residents.

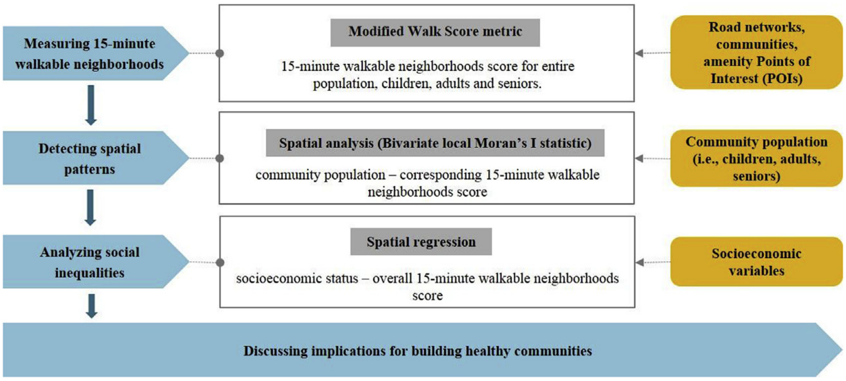

Fig. 3. Methodological flow chart.

4. Methodology

4.1. Methodological framework

The methodological framework is shown in Fig. 3, which includes 4 main steps:

(1) measuring 15-min walkable neighborhoods for different pedestrian groups (i.e., the entire population, children, adults, and seniors) through modifying the Walk Score metric;
(2) examining spatial patterns of 15-min walkable neighborhoods score for four population groups, and then analyzing mismatches between community population and their corresponding 15-min walkable neighborhoods score using spatial analysis (bivariate local Moran's I statistic in particular);
(3) exploring associations between community socioeconomic status and 15-min walkable neighborhoods score through spatial regression, and then analyzing social inequalities; and
(4) discussing implications for building healthy communities in urban China.

4.2. Measurement of 15-min walkable neighborhoods by modifying the Walk Score metric

Walk Score metric calculation takes four steps (https://www.walkscore.com): (1) assigning raw weights for selected amenities; (2) calculating distances from each location to the selected amenities; (3) computing the total scores based on the distances and modifying the scores according to decay factors (e.g., street intersections and block length); and (4) normalizing scores to 0–100. However, the metric has been criticized for incorporating three obvious limitations (Su et al., 2017a). First, it targets at overall population and the walking demands of different pedestrian groups have not been included in the assessment. Second, the decay effect of amenity varies greatly among population groups and categories of amenities. Third, actual traffic situation has not been considered when calculating distances based on Euclidean distance. In this regard, we propose a modified method to measure 15-min walkable neighborhoods based on the Walk Score metric, taking into account pedestrians' characteristics and amenity attributes

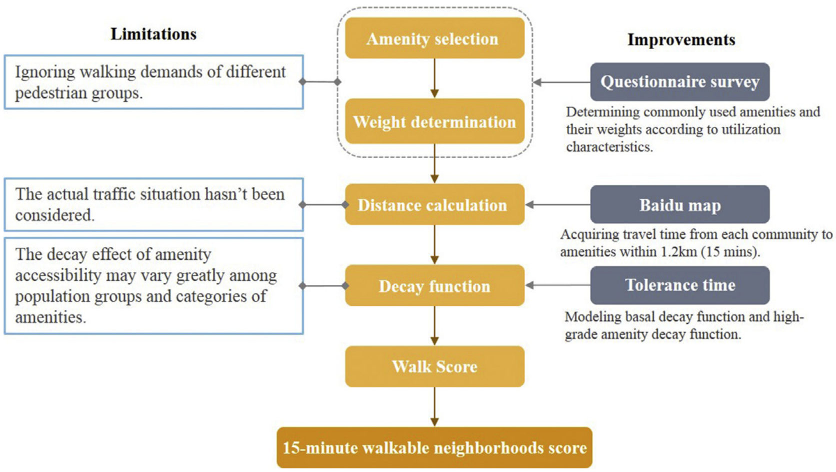

Fig. 4. Measurement of 15-min walkable neighborhoods through modifying the Walk Score metric.

(scale and category) (Fig. 4). Details for each step are provided as follows:

4.2.1. Amenity selection and weight determination

Considering that residents' neighborhood activity behaviors can be influenced by individuals' gender, age, occupation, and income (Brondeel et al., 2016; Moniruzzaman et al., 2013; Paez et al., 2013), we employed questionnaire survey to characterize walking demands of different pedestrian groups. First, based on the Shanghai Planning Guidance for 15-min walkable neighborhoods, we considered 6 categories of amenities, including education, medical care, municipal administration, finance and telecommunication, commercial services, and elderly care. We delivered the questionnaire (for details, see Supplemental Materials) on the Internet and recruited volunteers online. All the volunteers were self-referred and could completed the questionnaire according to personal realities. The survey covered 132 respondents (6.1% 6–12 years old, 9.1% 13–18 years old, 40.9% 19–40 years old, 32.6% 41–60 years old, 11.3% > 60 years old). Respondents reported the number of times per week (or month) that they generally participate in specific neighborhood activities, as well as amenities that they would like to reach within 5 min, 5–10 min and 10–15 min walking distance of their communities separately. The commonly used amenities and their weights (totaling up to 15) for all groups are determined using the outcomes of the questionnaires (Table 2).

4.2.2. Travel time calculation

To acquire more authentic travel times from each community to amenities within 15-min walking distance, we resort to the Baidu Map (https://map.baidu.com/). Baidu Map equips with fast updated and precise geodata. It is argued that Baidu Map can provide optimal route planning for specific transport modes in the actual road network (Chen et al., 2019; Xu et al., 2017). In addition, it can accurately predict the door-to-door distance according to real-time traffic conditions such as sidewalks and traffic lights (Su et al., 2017b).

4.2.3. Decay function

We adopt the tolerance time method (Su et al., 2017a; Xu et al., 2017) by considering pedestrians' mobility and amenity attributes (scale and category) to determine the decay function. Tolerance time represents the time threshold that a person can accept to reach facilities. Walking time is divided into three periods: < 5 min, 5–10 min, and 10–15 min. For each pedestrian group, we calculate the proportion of people who would like to reach an amenity within each time period. For each category of amenities (high, medium, and low utilization frequency), we get an average rate in each time period (3 digits in total for each group) and use the Gaussian function to model the basal decay function. The coefficient does not decline within 5 min but continuously decreases to 0 at the end of 15 min. The decay rate R(t) is calculated by Eq. (1). Besides, considering that due to requirements for high quality of life, people prefer to visit high quality amenities, for instance, high quality parks (Xu et al., 2017; Wang and Lan, 2019), we suppose that high-grade (top-ranking) amenities such as tertiary hospitals, district parks, exemplary schools (schools with superior teaching quality and running condition), district cultural and sports venues, and large geracomiums (nursing homes) can still attract people to utilize them even if they are relatively far away from communities compared with ordinary amenities. Therefore, we get the decay function for high-grade amenities, which the rate decays more slowly (Fig. 5). Specifically, the entire population has the same decay function as adults.

$$R(t) = \begin{cases} 1 & if\ t \le 5\ min \\ y_0 + ae^{-\frac{(t-b)^2}{2c^2}} & if\ 5 < t \le 15\ min \end{cases} \tag{1}$$

where y_0, a, b, and c are real constants, expected value $\mu = b$, $b = 5$, and variance $\sigma^2 = c^2$.

4.2.4. Score normalization

After assembling initial score, we normalize the score into 0–100 (Table 3). Specifically, higher scores correspond to communities that are regarded as more conducive to walking. Thus, we obtain the neighborhoods' 15-min walkability score for the entire population and for children, adults, and seniors.

4.3. Spatial analysis

The bivariate local Moran's I statistic (Mathematical details, see Hu et al., 2019) is performed to identify the spatial patterns of 15-min walkable neighborhoods. In our study, the statistic captures the correlation between the proportion of a pedestrian group within one certain community and the corresponding 15-min walkable neighborhoods score. More specifically, it can be used to detect spatial cluster and spatial outliers. The "high-high" clusters (proportion of population at a location and corresponding score at the surrounding places are both high) and "low-low" clusters (proportion of population at a location and corresponding score at the surrounding places are both low) indicate a significant positive spatial correlation between the population and 15-min walkable neighborhoods score. Besides, spatial outliers contain the "high-low" outliers (high proportion of population in a low corresponding score surroundings) and "low-high" outliers (low proportion of population in a high corresponding score surroundings) indicate mismatches of the 15-min walkable neighborhoods. The bivariate local Moran's I statistic is calculated using a spatial weights matrix based on nearest neighbor's distance.

1. weight的意义？怎么算的？

Table 2
Amenities for 15-min walkable neighborhoods measurement of entire population (a), children (b), adults(c), and seniors (d).

(a)

Principle category	Sub-category	Third level	Weight
Education	School	Kindergarten	0.6
		Primary school	0.6
		Middle school	0.6
	Training institution		0.5
Medical care	Hospital	Hospital	0.4
		Neighborhood health center	0.5
	Pharmacy		0.6
Municipal administration	Public transport site	Metro entrance (0.75), Bus stop (0.75)	1.5
	Park and square		1
	Sports venue	Neighborhood fitness court	1
		Indoor stadium	0.5
	Cultural venue	Library, Art museum, Art gallery, Cultural center	0.5
		Neighborhood cultural activity center	0.6
Finance and telecommunication	Finance	Bank, ATM	0.5
	Post office		0.4
Commercial service	Restaurant		0.8
	Shopping	Fresh market	0.9
		Small and medium-sized store (Convenience store (0.65), Fruit store (0.65))	1.3
		Large store (Supermarket (0.5), Department store (0.3))	0.8
	Entertainment venue	Beauty salon (0.05), KTV (0.05), Cinema (0.08), Gym (0.08), SPA (0.07), Amusement Park (0.05), Children's park (0.05), Café (0.07)	0.5
Elderly care	Geracomium (Nursing home)	Geracomium (0.2), Apartment for seniors (0.2)	0.4
	Elderly education	School for older adults	0.5

(b)

Principle category	Sub-category	Third level	Weight
Education	School	Kindergarten	2
		Primary school	2
		Middle school	2
	Training institution		1.2
Medical care	Hospital	Hospital	0.8
		Neighborhood health center	1
Municipal administration	Public transport site	Metro entrance (0.9), Bus stop (0.9)	1.8
	Park and square		1.5
	Sports venue	Neighborhood fitness court	1.2
	Cultural venue	Library, Art museum, Art gallery, Cultural center	0.7
Commercial service	Entertainment venue	Cinema (0.3), Amusement Park (0.2), Children's park (0.3)	0.8

(c)

Principle category	Sub-category	Third level	Weight
Education	School	Kindergarten	1.8
		Primary school	1.6
Medical care	Hospital	Hospital	0.4
		Neighborhood health center	0.5
	Pharmacy		0.5
Municipal administration	Public transport site	Metro entrance (1), Bus stop (1)	2
	Park and square		0.6
	Sports venue	Neighborhood fitness court	0.8
		Indoor stadium	0.5
	Cultural venue	Neighborhood cultural activity center	0.5

(*continued on next page*)

Table 2 (*continued*)

(a)

Principle category	Sub-category	Third level	Weight
Finance and telecommunication	Finance	Bank, ATM	0.4
	Post office		0.3
Commercial service	Restaurant		1
	Shopping	Fresh market	1.2
		Small and medium-sized store (Convenience store (0.8), Fruit store (0.8))	1.6
		Large store (Supermarket (0.5), Department store (0.3))	0.8
	Entertainment venue	Beauty salon (0.05), KTV (0.05), Cinema (0.1), Gym (0.1), SPA (0.1), Café (0.1)	0.5

(d)

Principle category	Sub-category	Third level	Weight
Education	School	Kindergarten	1.2
		Primary school	0.9
Medical care	Hospital	Hospital	0.5
		Neighborhood health center	0.6
	Pharmacy		0.4
Municipal administration	Public transport site	Metro entrance (0.6), Bus stop (0.6)	1.2
	Park and square		1.5
	Sports venue	Neighborhood fitness court	0.8
		Indoor stadium	0.4
	Cultural venue	Library, Art museum, Art gallery, Cultural center	0.3
		Neighborhood cultural activity center	0.7
Finance and telecommunication	Finance	Bank, ATM	0.3
	Post office		0.3
Commercial service	Restaurant		0.8
	Shopping	Fresh market	2
		Small and medium-sized store (Convenience store (0.5), Fruit store (0.5))	1
		Large store (Supermarket)	0.7
	Entertainment venue	SPA	0.5
Elderly care	Geracomium (Nursing home)	Geracomium (0.2), Apartment for seniors (0.2)	0.4
	Elderly education	School for older adults	0.5

4.4. Spatial regression

Spatial regression is used to explore associations between the community socioeconomic status and 15-min walkable neighborhoods score. We first analyze the association between three age variables (proportion of children, adults, and seniors) with their corresponding score; and then analyze all the socioeconomic variables in relation to the overall 15-min walkable neighborhoods score. The spatial lag (Eq. (2)) and spatial error (Eq. (3)) models are two forms of spatial regression models (Anselin, 1988) whose estimation is fitted through the maximum likelihood (ML) algorithm (Anselin and Bera, 1998).

$$Y = X\beta + \rho W_Y + \varepsilon \tag{2}$$

$$Y = X\beta + u,\ \ u = \rho W_u + \varepsilon \tag{3}$$

where Y is the response variable, X is the explanatory variable, β is the regression coefficients of the explanatory variable, ρ is the spatial autoregressive coefficient, W_Y and W_u constitute the spatial weight matrix, and ε is the error term. The spatial matrix is constructed using the nearest neighbor's distance matrix.

5. Results

5.1. Spatial patterns of 15-min walkable neighborhoods

Fig. 6 shows the uneven distribution of 15-min walkable neighborhoods score for different pedestrian groups. As for the entire population (Fig. 6a), a few moderately to highly walkable communities (walkability score ≥ 50) are primarily concentrated around the urban core, while the majority of communities outside central city are characterized by inferior walkability (walkability score ≤ 24). In terms of children's walkability (Fig. 6b), a small number of communities with higher walkability (walkability

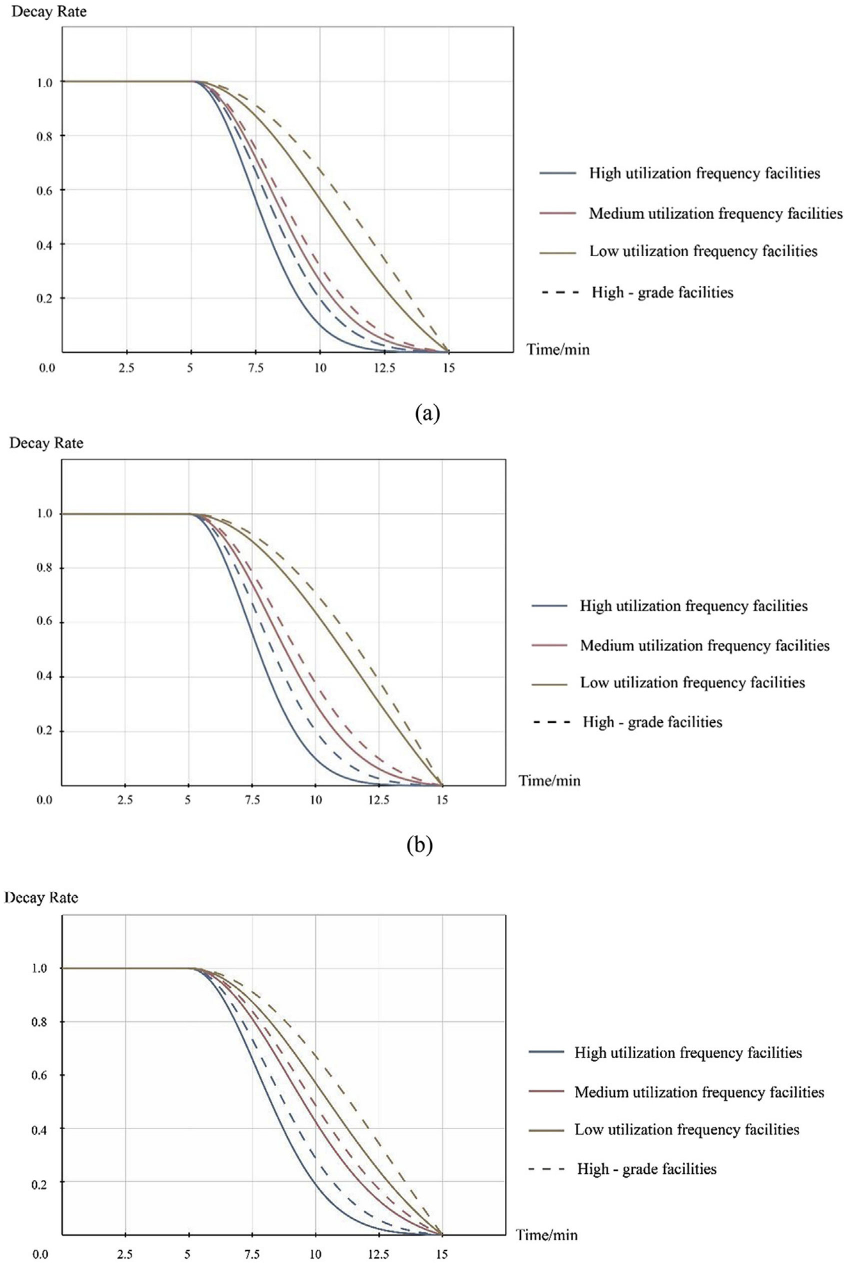

Fig. 5. Type of decay function for children (a), adults\entire population (b), seniors (c).

Table 3
Grade of the 15-min walkable neighborhoods score.

Score	Description
90–100	Highly walkable. Daily trips do not rely on a vehicle.
70–89	Very walkable. The majority of daily trips rely on walking.
50–69	Moderately walkable. Part of daily trips rely on walking.
25–49	Somewhat walkable. The majority of daily trips rely on a vehicle.
0–24	Car-Dependent. Nearly all daily trips rely on a vehicle.

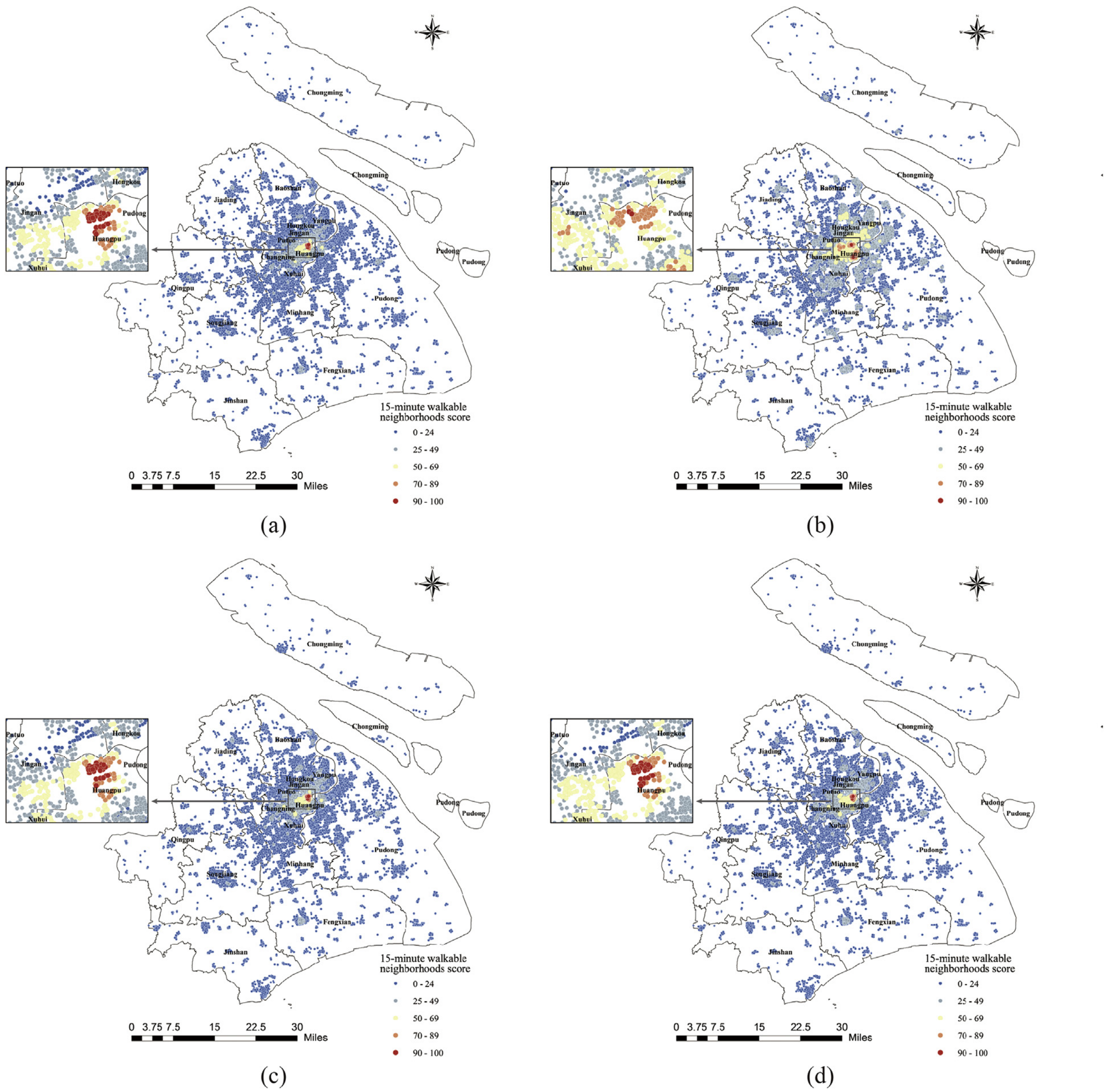

Fig. 6. 15-minute walkable neighborhoods score for entire population (a), children (b), adults (c), and seniors (d).

score ≥ 50) are located in the city center, and somewhat walkable communities (25 ≤ walkability score ≤ 49) distribute in central districts and some suburban centers. Non-walkable communities (walkability score ≤ 24) are dispersed in peripheral urban areas. Results for adults (Fig. 6c) and seniors (Fig. 6d) present similar patterns with the overall population, that is, 15-min walkable neighborhoods score is higher in the central areas but gradually decline in the outskirts.

The results of the bivariate cluster analysis are shown in Fig. 7. With respect to children (Figs. 7a), 2365 communities (18.10%) are "low-high" outliers, and these communities are mostly located in the urban center. The "high-low" outliers (2167, 16.59%) are situated within the suburbs and are characterized by a high proportion of children embedded in areas that offer low walkability for children. Less than one-tenth of all communities belong to "high-high" (238, 1.82%) and "low-low" (919, 7.04%) clusters, and they are located in central city and rural areas, respectively. As for adults (Fig. 7b), a distinctly higher number of "high-high" clusters (1618, 12.39%) and "low-low" clusters (1855, 14.20%) exist compared with those for children, and these clusters emerge in the central part of the city and outskirts separately. The "low-high" and "high-low" outliers emerge in the city's center and rural districts respectively, and they are relatively few. In the case of seniors (Fig. 7c), "high-high" clusters (1836, 14.05%) and "low-high" outliers are in the urban center, while the "low-low" clusters (2428, 18.59%) and "high-low" outliers are located within the suburbs. The results contribute to the better and more accurate display of mismatches of 15-min walkable neighborhoods score among different

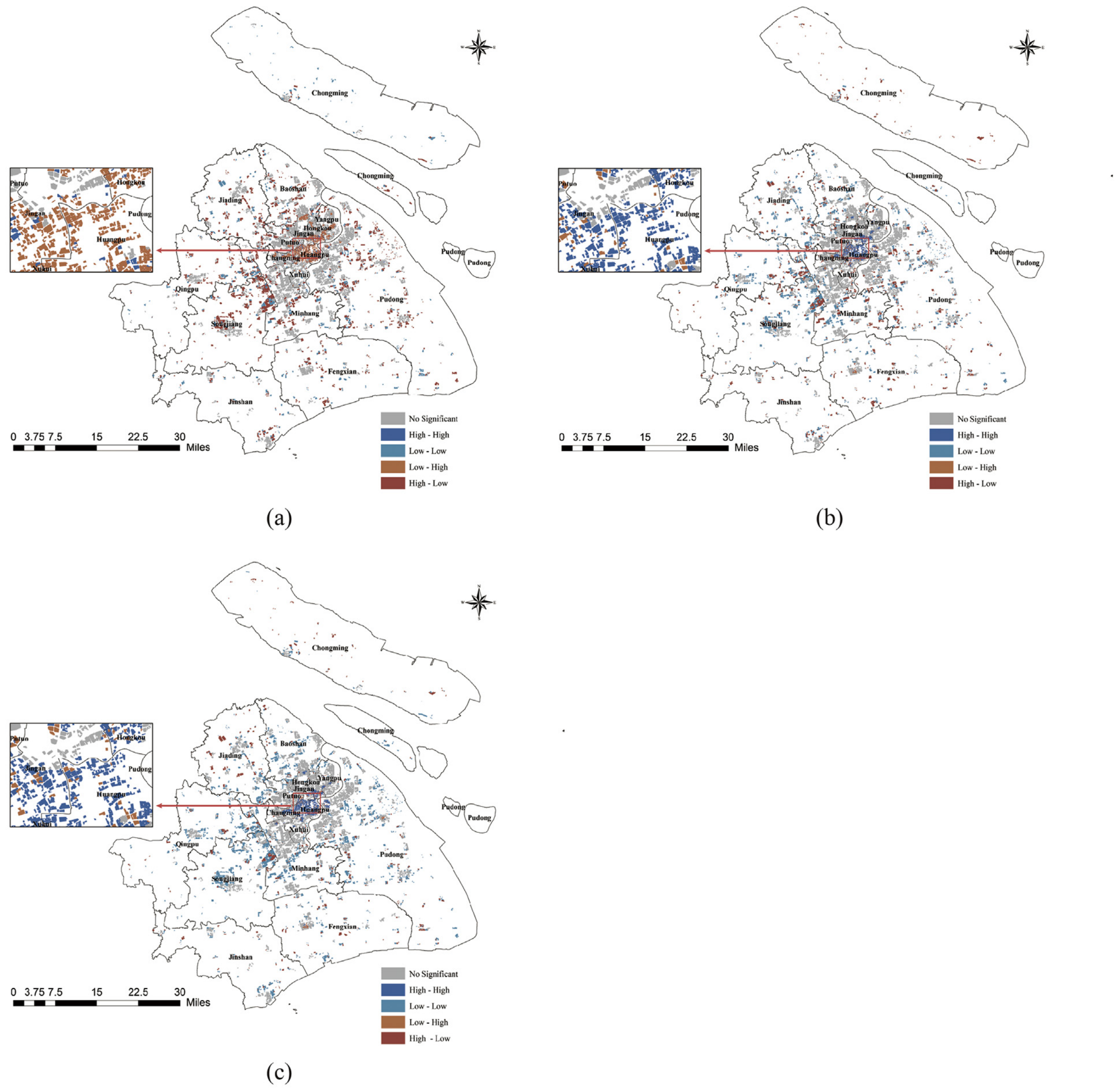

Fig. 7. Local spatial patterns (Bivariate local Moran's I) between proportion of children and 15-min walkable neighborhoods score of children (a), proportion of adults and 15-min walkable neighborhoods score of adults (b), proportion of seniors and 15-min walkable neighborhoods score of seniors (c).

pedestrian groups. It suggests that daily needs of adults and seniors can typically be satisfied via walking within 15-min walkable neighborhoods.

5.2. Social inequalities in the 15-min walkable neighborhoods

Table 4 shows the associations between the proportion of each pedestrian group and their 15-min walkable neighborhoods score. Proportion of adults and proportion of seniors are positively correlated with their walkability score, while proportion of children is not. Table 5 shows the relationships between total 15-min walkable neighborhoods score and socioeconomic status variables. All the variables are significantly correlated with walkability score. The 15-min walkable neighborhoods score is negatively associated with proportion of children and non-registered (floating population, namely, nonresidents), but is positively associated with proportion of adults, seniors, females, minorities, separation of registered and actual residence, and agricultural registered. It indicates that communities predominantly containing adults and seniors are potentially characterized by higher walkability. However, children-concentrated and floating-concentrated communities are more likely to have lower walkability, indicating the potential for

Table 4
Relationships between 15-min walkable neighborhoods score of each age group and demographics identified by spatial regression (N = 13063).

Sociodemographic variables (X)	Regression equation	R^2
% Children	$Y^{a,b} = -0.54 \times X + 0.35 \times W_Y + 48.98$	0.40**
% Adults	$Y^{a,c} = 0.31 \times X + 0.43 \times W_Y + 0.11$	0.33**
% Seniors	$Y^{a,d} = 0.68 \times X + 0.40 \times W_Y + 6.21$	0.38**

**$p < 0.01$.
[a] Spatial lag regression: W_Y is the spatial weight for Y.
[b] Y is for the children.
[c] Y is for the adults.
[d] Y is for the seniors.

Table 5
Relationships between overall 15-min walkable neighborhoods score and socioeconomic status variables identified by spatial regression (N = 13063).

Socioeconomic variables (X)	Regression equation	R^2
% Children	$Y^{a} = -0.34 \times X + 0.40 \times W_Y + 30.03$	0.37**
% Adults	$Y^{a} = 0.32 \times X + 0.44 \times W_Y - 0.33$	0.34**
% Seniors	$Y^{a} = 0.66 \times X + 0.40 \times W_Y + 5.67$	0.38**
% Females	$Y^{a} = 0.39 \times X + 0.43 \times W_Y - 6.95$	0.35**
% Minorities	$Y^{a} = 0.03 \times X + 0.45 \times W_Y + 11.77$	0.31**
% Separation of registered and actual residence	$Y^{a} = 0.66 \times X + 0.30 \times W_Y + 8.27$	0.58**
% Non-registered	$Y^{a} = -0.16 \times X + 0.42 \times W_Y + 11.93$	0.37**
% Agricultural registered	$Y^{a} = 1.05 \times X + 0.43 \times W_Y - 91.06$	0.34**

**$p < 0.01$.
[a] Spatial lag regression: W_Y is the spatial weight for Y.

inequalities in 15-min walkable neighborhoods.

6. Discussion and conclusions

6.1. Social inequalities in 15-min walkable neighborhoods

Walkability measurement is greatly subjected to the demands of varying pedestrian groups. This study develops a practical method for measuring 15-min walkable neighborhoods through modifying the Walk Score metric. The measurement considers different behavior characteristics of four pedestrian groups (the entire population, children, adults, and seniors) and facility attributes (scale and category). It corresponds to previous require that the variability in walkability measurement should be examined in relation of subject, walking purpose, and living condition (Day, 2016; La Rosa et al., 2018; Todd et al., 2016; Moura et al., 2017). In particular, we have made three essential improvements in walkability measurement. First, we employ questionnaire survey to determine commonly used amenities and their weights for different pedestrian groups (the entire population, children, adults, and seniors). Second, Euclidean distance from community to each destination is substituted by actual travel time obtained from Baidu Map. Finally, we utilize tolerance time method to develop decay functions for varying pedestrian groups and different categories of amenities.

We further examine the geographic disparities in 15-min walkable neighborhoods among the communities within Shanghai city, China. Highly walkable communities are mainly concentrated in the central areas, and poorly walkable communities dispersed in rural areas. This trend has been observed for the four groups of people, including the entire population, children, adults, and seniors. Such discovery is consistent with prior studies conducted in the inner-city neighborhoods in cities of western countries (Bereitschaft, 2017; Gilderbloom et al., 2015; Jun and Hur, 2015) and in Shenzhen city of China (Su et al., 2017a). It also supports the argument that the old central district in Shanghai, with its small neighborhoods and dense streets, is pedestrian friendly (Fan et al., 2018). Besides, this result is related to findings that central districts present higher walking accessibility to public services in several China's cities (Hu et al., 2019; Zeng et al., 2019). In addition, the "high population proportion, low walkability" outliers and "low population proportion, high walkability" outliers are detected in areas where residents' everyday life necessity and walkable accessibility are mismatched and are situated in peripheral suburban areas and the city's center, respectively. Particularly, the "high-low" outliers, representing the less developed areas, require urgent investment to construct 15-min walkable neighborhoods, which is especially important for children because the results indicate that they have the largest number of "high-low" outliers compared with adults and seniors. As housing prices soar in the central urban districts, the increasing number of middle and low-income families tend to live in the suburbs where housing values are lower and traffic is remarkably enhanced. Furthermore, with the acceleration of urbanization and industrialization, the government establishes many new development zones and industrial parks in suburbs which attract a great many peasant workers (Tian et al., 2017). Therefore, residents generate sharply increasing needs for commonly used amenities, such as parks, hospitals, sports venues, schools, and public transit sites. However, these needs cannot be satisfied at present, which simultaneously leads to constrained opportunities and access to fundamental public services and resources via walking within 15-min walkable neighborhoods and reflects spatial inequalities among communities.

Our study evidences that significant social inequalities exist in the 15-min walkable neighborhoods. Spatial regression shows that the 15-min walkable neighborhoods score is positively correlated to proportion of adults and seniors, but is negatively correlated to proportion of children and floating population. We find that high proportion of children would be observed in less walkable communities, which is accordant with previous findings (Cutts et al., 2009; Su et al., 2017a). Meanwhile, our finding supports the conclusion that children may have limited access to public facilities, such as green spaces, schools, and food-retailing outlets (Macdonald et al., 2016; Ravensbergen et al., 2016; Reyes et al., 2014; Xu et al., 2017), but literature has reported that the majority of children live in school catchment neighborhoods in Shenzhen city of China (Sun et al., 2018). However, adults are greatly presented in highly walkable communities, suggesting that an adult-orientated friendly walking environment may be less advantageous for children. Recent researches similarly indicate that seniors are in a good walking environment with high amenity accessibility (Boakye-Dankwa et al., 2019; Hirsch et al., 2017; Li et al., 2019a; Su et al., 2017a); in contrast, negative association between neighborhood walkability and proportion of seniors has been explored by Bereitschaft (2017) in U.S. cities, indicating that socio-economic differences in walkability vary by urban contexts. Additionally, we demonstrate that communities where residents are predominately floating population tend to have inferior walkability. The conclusion that floating population (primarily consist of migrant workers) may have unequal access to desirable public services and resources, dwelling condition, and medical care (Wan and Su, 2017; Weng et al., 2017; Xu et al., 2017; You, 2016) has been borne out by our research. It is argued that spatial inequalities in neighborhood walkability are partly resulted by residential segregation (Duncan et al., 2008). Young couples may be more prone to settle down in the suburbs where real estate development precedes the construction of supporting infrastructure within the neighborhood due to the restricted capability of these couples to purchase houses in the city's center (Su et al., 2017a). In addition, elders usually live in communities in the old city core where dwellers have convenient accessibility to diversified public facilities (Li et al., 2019a; Liu et al., 2014), thereby contributing to high walkability. Economically disadvantaged migrants generally live in low-rent houses in suburbs where neighborhoods are characterized by very sparse fundamental public facilities (Yang et al., 2015), thus leading to low walkability. In conclusion, our research indicates that endeavors to build 15-min walkable neighborhoods in urban areas must take social equality into consideration seriously.

6.2. Implications for building healthy communities in urban China

Our study highlights the social inequalities in 15-min walkable neighborhoods and delineate the non-walkable communities in the suburban part of Shanghai. Non-walkable neighborhoods featured by low residential density, poorly-connected street networks, and fragmented land use can reduce residents' motivations in physical activities, are thus not beneficial for overall health promotion (Fan et al., 2018; King et al., 2011; Lovasi et al., 2011). Therefore, we argue that four aspects should be emphasized for building walkable and healthy communities: (1) providing full coverage service assurance, (2) building a continuous and pedestrian-friendly street network, (3) forming a compact and accessible layout, and (4) developing affordable housing.

First, ensuring all residents' basic daily demands in neighborhoods is conducive to developing a healthy living environment. The priority is to construct basic supporting amenities (e.g., schools, neighborhood health service centers, and parks) for residents who live in suburban neighborhoods. Moreover, the facilitation of high-grade amenities is optional but beneficial in moderately to highly walkable neighborhoods to promote residents' quality of life. The current study reflects the necessity for focusing on life convenience for children and floating population. Thus, equitable community initiatives should specifically put emphasis on needs of such vulnerable groups.

Second, directing funds into streetscapes to build safe and walkable streets is equally important. Improving pedestrian-related built environment attributes may significantly promote walkability in underdeveloped suburbs (Fan et al., 2018). Planning policies should consider offering marked crosswalks and barrier-free paths, building flat sidewalks and simultaneously controlling their width, planting street trees, and installing lighting to improve the comfort of the pedestrian network (Gilderbloom et al., 2015). In addition, it is assumed that developing a complete and continuous pedestrian network will reduce pedestrians' insecurity and encourage more walking (Moniruzzaman and Paez, 2016).

Third, forming a compact and accessible layout relates to land use planning. A highly walkable neighborhood is bound up with abundant and various functional zones that can be conveniently accessed on foot (Pliakas et al., 2014). A compact layout is recognized as enhancing walking by providing more direct and shorter paths to destinations (Khattak and Rodriguez, 2005; Song et al., 2013). Also, walking accessibility should be regarded as an important indicator in future neighborhood-scale planning (Zuniga-Teran et al., 2016).

Finally, the proportion of economically affordable housing and rental housing should be increased. Since high walkability is usually companied by high housing values in downtown neighborhoods (Tong et al., 2016; Yang et al., 2018). Developing rental and affordable housing policies may provide equal opportunities for economically disadvantaged people to access walkable amenities (Yang et al., 2015), further helping to eliminate social inequalities. The proposed suggestions may bring some useful insights to planners and policymakers in the domain of urban planning and public health to achieve socially equal, walkable, and sustainable cities.

6.3. Limitations and prospects

The study of social inequalities in 15-min walkable neighborhoods could be developed in the future by selecting some health outcomes (e.g., obesity, cardiopathy, hypertension, and diabetes) and deprivation indicators (e.g., unemployment, low income, and less education); that is, exploring the associations among 15-min walkable neighborhoods score, public health, and social deprivation, may provide an orientation for building 15-min walkable neighborhoods to promote residents' health and eliminate social inequalities. In addition, some elements of built environments, such as pedestrian infrastructures (e.g., sidewalks, paths, and street lighting), safety factors, and the attractiveness of the pedestrian environment, which are well documented in existing studies (Moura et al., 2017), can be taken into consideration to modify the measurement of 15-min walkable neighborhoods. Also, different modes of travel behaviors, different environment, and even different life styles in the center and suburbs are not noticed in our study. Lack of information on whether varied walking characteristics exist when children walk alone or with parental accompany (Sun et al., 2018) limits this research as well. Thus, the associations between walkability measures and actual walking behavior need be taken into consideration in the future. Finally, a validation study, such as a survey, should be carried out in future research to prove the reliability and validity of the overall assessment method of 15-min walkable neighborhoods.

Acknowledgement

Funding support of this study originates from the Humanity and Social Science Youth Foundation of Ministry of Education of China (No. 15YJC890036) and the Fundamental Research Funds for the Central Universities (No. 2042018kf0223).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jth.2019.05.005.

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