https://doi.org/10.15302/J-LAF-1-020075

Research of the Influence Mechanisms of Green Infrastructure on Walking Physical Activities in Changsha–Zhuzhou–Xiangtan Urban Agglomeration, China

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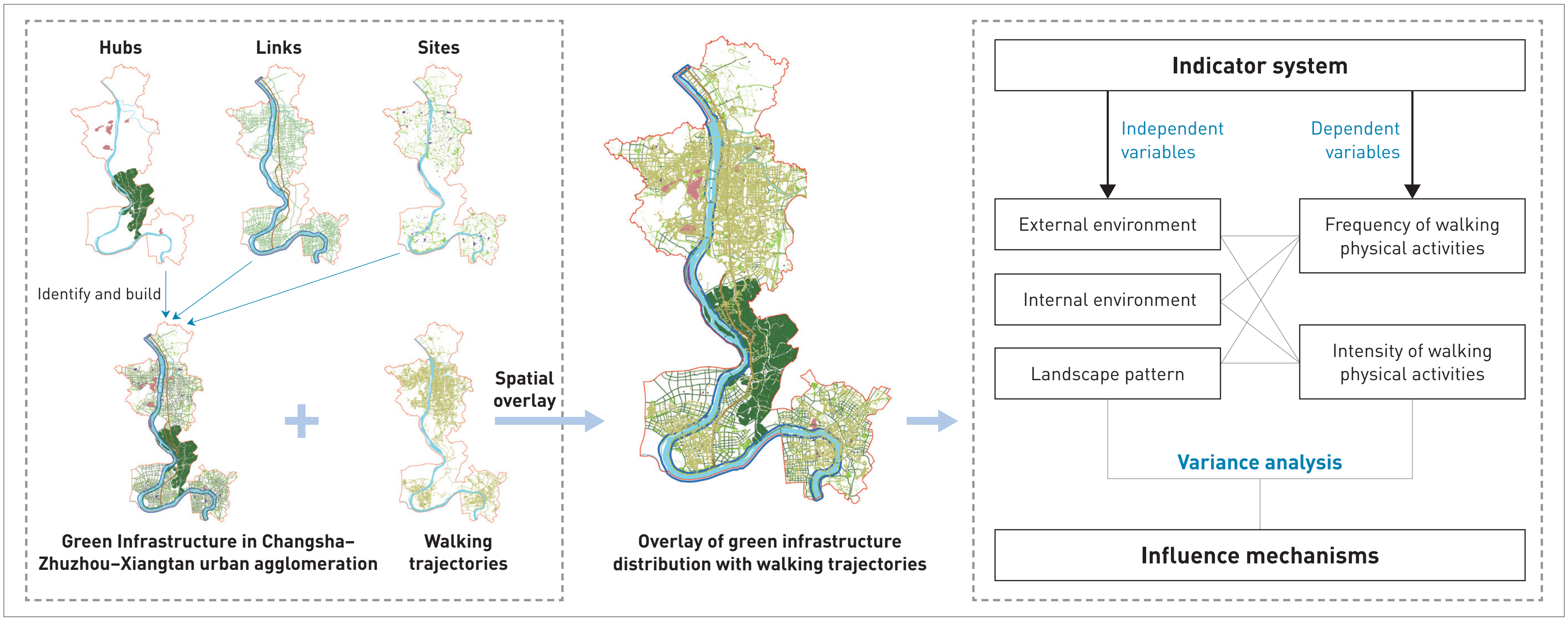
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Walking trajectories aggregated in links and sites of green infrastructure in Changsha–Zhuzhou–Xiangtan urban agglomeration
- The impacts of internal environment, external environment, and landscape pattern of green infrastructure on walking physical activities vary
- Proposes suggestions for urban construction and renovation of green infrastructure in the urban agglomeration

KEYWORDS

Green Infrastructure;
Walking Physical Activity;
Influence Mechanism;
Changsha–Zhuzhou–Xiangtan Urban Agglomeration;
Spatial Pattern

RECEIVED DATE

2023-04-21

ABSTRACT

Walking physical activities can improve people's health, for which exploring the influence mechanisms of green infrastructure on walking physical activities is important to the creation of healthy urban environment. This paper focuses on the relationship between green infrastructure in Changsha–Zhuzhou–Xiangtan urban agglomeration of China and the frequency and intensity of walking physical activities. The research first identified the elements of green infrastructure (i.e. hubs, links, and sites) and studied the spatial distribution of walking trajectories, then constructed the indicator system from perspectives of the internal environment, external environment, and landscape pattern of green infrastructure in the urban agglomeration, and employ the multiple linear regression model to analyze the influence mechanisms of green infrastructure on the frequency and intensity of walking physical activities. The results suggest that the walking physical activities mostly overlapped with the links and sites, and the indicators impact residents' walking physical activities differently. Housing density, housing price, public toilet density, urban plaza density, bus stop density, percentage of green spaces, large patch index, and aggregation index all have significant correlations with both the frequency and intensity; land use mix, average daily temperature, and percentage of water body area only have significant correlations with intensity; and, path density only has a significant correlation with frequency. Based on the findings, this paper proposed suggestions for urban construction and renovation in aspects of internal environment, external environment, and landscape pattern, respectively, aiming to improve the cities' walking environment, and boost the social and ecological values of green infrastructures in the urban agglomeration.

EDITED BY
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1 Introduction

With the rapid development of cities, the global incidence of many chronic diseases is on the rise. At present, the number of chronic diseases occurring in China has exceeded 200 million, accounting for more than 20% of the total population[1]. According to the report by World Health Organization in 2014, there were about 40 million deaths caused by chronic diseases each year worldwide, accounting for 70% of the total number of deaths. It is estimated that this number will reach 55 million by 2030[2]. Walking physical activities can help reduce the risks of chronic diseases and improve residents' health and the quality of life[3]~[5]. Existing studies have demonstrated that walking environment conditions can affect people's walking physical activities in frequency and intensity, thereby, influencing their physical (e.g., BMI) and mental health[6]~[12].

Green infrastructure (GI) is a network consisting of connected natural areas and other green open spaces and the accessory engineering infrastructure[13][14]. The elements of GI are usually categorized as hubs, links, and sites[15][16]. GI is characterized by systematic, networking pattern and high accessibility, and can provide low-cost, nature-friendly outdoor exercise places and recreational spaces[17] for walking physical activities[18]. In 2016, the National Recreation and Park Association of the USA surveyed residents on the use of parks and recreational facilities, and the results showed that approximately 52% of respondents preferred to take their daily physical activities in GI such as parks and urban plazas[19].

Current research mainly examines the relationship between GI and a single attribute of physical activities, which investigated the landscape characteristics (e.g., accessibility[20][21]) of different elements of GI (e.g., urban green space and water bodies), the number and types of infrastructure[22], the design of pathway networks[23], etc. Christopher Coutts et al. found that an increase in the number of green spaces would positively affect residents' willingness to engage in physical activities[24]. The research by Fuzhong Li et al. showed that the increase of housing density, number of green and open spaces, and path crossings would enhance people's willingness to walk continuously[25]. It is revealed in the research by Abdullah Akpinar et al. and Jasper Schipperijn et al. that the frequency of walking physical activities decreases with the increasing distance between GI[26][27]. The studies by

Thomas Astell-Burt et al. and Christopher Coutts et al. prove that with the increased number of GI and reduced distance between GI, the frequency of adults carrying out physical activities of different intensity would all increase[22][24]. Existing studies on overall GI put more efforts into inspecting the impact of spatial patterns on human production and living activities[28] and its correlations with living environment quality and human health[29], while less on walking physical activities. Therefore, there is a research gap of the correlation between GI spatial patterns and walking physical activities, and further analysis of the differences and influence mechanisms of GI on the frequency and intensity.

Urban agglomeration refers to an economic region centering one or two megacities with the surrounding cities, which has close internal economic connections and is supported with developed and integrated regional infrastructure[30]. The permanent resident population in China's urban agglomerations already accounts for 64.6% of the country's total population[31]. This means that GI in urban agglomerations would play a major role in ensuring urban and rural residents' walking physical activities. The existing studies on GI in urban agglomerations focus on the construction of green space systems[32]~[34], protective development of green hearts[35], formation of landscape security pattern[36], green space evaluation[37][38], etc. A number of studies have shown that GI in urban agglomerations can fulfill diverse needs for exercise, improve public health, promote the quality of human living environment, and encourage social interaction by optimizing the cities' ecological pattern[33][39]~[41].

Aiming to further understand the correlation between GI in urban agglomerations and walking physical activities, this paper focuses on GI and residents' walking physical activities in the Changsha–Zhuzhou–Xiangtan urban agglomeration (CZX urban agglomeration hereafter) in China. The research team applied the multiple linear regression model for variance analysis, to explore the influence mechanisms of GI on frequency and intensity of walking physical activities, and proposed suggestions to promote walking and to construct healthy urban environment, which can be conducive to enhancing human well-beings.

2 Research Methods

2.1 Study Area

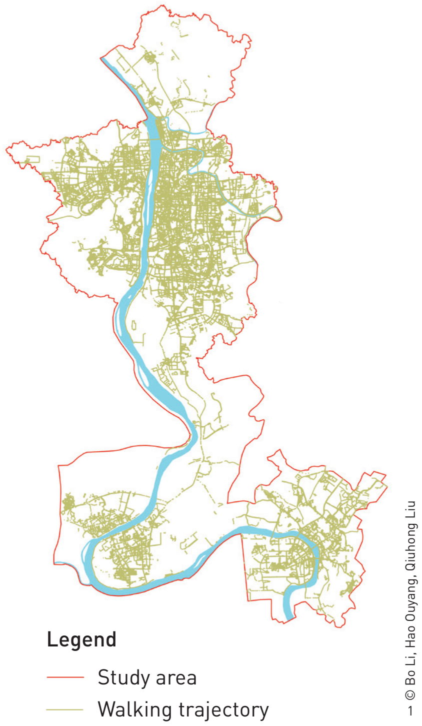
The study area of this research is the central area of CZX urban agglomeration in Hunan Province, China. It includes Tianxin, Furong, Kaifu, Yuhua, and Yuelu Districts in Changsha City, Tianyuan, Lusong, Shifeng, and Hetang Districts in Zhuzhou City, and Yuetang and Yuhu Districts in Xiangtan City. The CZX urban agglomeration has a total area of about 1,260.65 km^2 (Fig. 1)①. In 2021, the permanent population in the study area was 16.8316 million. With an urbanization rate of 77.70%, CZX urban agglomeration is the economic growth pole of Hunan Province[42].

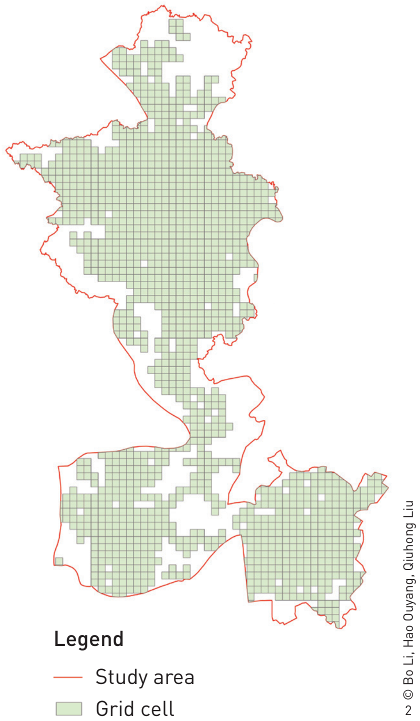
2.2 Data Sources

The walking physical activity data used in this research was sourced from the app "DuoRui" that covered the period from 2016 to 2019. DuoRui is a sports and health application mainly used by young and middle-aged users②. During the study period, there were 3,785 users in the CZX urban agglomeration. This app combines algorithms with smart hardware for physical exercise detection and data analysis, and can generate professional evaluation reports with customized exercise plans. The raw data obtained included users' running and walking trajectories. Among them, 83% were walking data such as spatial position, type, duration, distance, date, and frequency of exercises, used in this research.

The urban land use classification data of the study area were obtained from the *Urban Comprehensive Planning of Changsha (2003–2020) (Revised in 2014), Urban Comprehensive Planning of Xiangtan (2010–2020) (Revised in 2017)*, and *Urban Comprehensive Planning of Zhuzhou (2006–2020) (Revised in 2017)*[43]~[45]. After raster vectorization of the maps, the data were adjusted and corrected according to the actual construction situation in 2020. The road network data were processed based on Open Street Map, also corrected according to the actual construction situation③. Average daily precipitation and average daily temperature data from 2016 to 2020 were obtained from the National Meteorological Information Center. Landsat 8 images of the study area as of December 2019 were downloaded from the USGS website to calculate the Normalized Difference Vegetation Index (NDVI). The average monthly housing price (2016 ~ 2019) was calculated based on three major real estate platforms in China, i.e. Anjuke, Home Link, and Fang, after

① The total area of CZX urban agglomeration was calculated referring to data on the website of People's Government of Hunan Province.
② The information about main user group was sourced from the team of DuoRui.
③ Researchers used Amap to compare the categorization of land use in planning documents and the road network obtained from Open Street Map with the actual situation of land use, road network, and infrastructures in 2020, and then corrected the vector data.





1. Distribution of the trajectories of walking physical activities
2. Distribution of grid cells

deduplication. Population data were obtained from China's seventh national census statistics by Hunan Provincial Bureau of Statistics. Based on the total population of each street in the study area and the corresponding number of households, the population of each neighborhood was corrected. Finally, the POI data (e.g., bus stops, public toilets, urban plazas, and parks) crawled from Amap in December 2019 were used after data correction and cleansing.

2.3 Analysis Methods

2.3.1 Delineation of the Scope of GI in the Urban Agglomeration

The widely accepted and applied method for delineating GI generally involves defining the objectives and functions of GI, determining its elements (hubs, links, and sites[15][16]), and identifying the pattern of GI networks[46].

Hubs are natural habitats that are patches being less disturbed with relatively larger areas, in forms of undeveloped lands, conservation areas, suburban parks, forests, lakes, wetlands, farmlands, pastures, and woodlands in the urban area[47]. The delineation of hubs requires a holistic assessment of regional development and conservation policies, integrating indicators such as patch size, number of species, and connectivity in GI patterns[48]. Thereby, the patches with better performance on such indicators could be identified as GI hubs[49].

Links are linear ecological corridors that connect hubs and sites, normally in forms of urban green spaces along rivers and roads, and protective green belts[50]. The location and extent of links can be delineated using GIS analysis and survey on the collection of various data such as ecological conditions, area, connectivity, and other regional statistics[51][52].

In addition to hubs and links, sites provide recreational places with both ecological and social values, in forms of small urban parks, plazas, roadside green spaces, and community parks/gardens in urban area[47]. Existing research relies on qualitative methods to identify sites after the delineating hubs and links[15][16][50]~[52]. With land use maps and urban POI data, this study identified sites by filtering various nodes such as green spaces and plazas that are closely connected with citizens' daily life.

2.3.2 Grid Cell Division

Grid analysis has been widely applied in landscape evaluation, environmental monitoring, and social analysis[53]~[55]. The subdivided grid cells can reflect the heterogeneity and spatial characteristics of the landscape, and further facilitate the integration and analysis of multi-source data. The grid scale in this study was based on the walking distance of a 10-minute life circle. Normally, the walking speed of people is 4.60 ~ 5.35 km/h, i.e. about 800 meters in 10 minutes. Referring to related studies[53][54], a grid system of 800 m × 800 m was created for the study area using the fishnet creation tool in ArcGIS 10.6. By overlaying with the layers of GI, 1,436 grid cells containing GI in the urban agglomeration were identified (Fig. 2).

2.3.3 Indicator System Construction

In order to better characterize the attributes of GI in urban agglomerations and systematically investigate the relationship between GI and walking physical activity, this paper constructed a GI indicator system for CZX urban agglomeration (Table 1) to obtain independent variables based on relevant research.[56]~[74] It included three categories: external environment, internal environment, and landscape pattern. External environment indicators include population, economic, and environmental subcategories. Although population and economic indicators are not direct constituents of GI, some existing studies have shown that they are significantly correlated as independent variables rather than control variables for physical activities[56]~[58]. Internal environment indicators refer to relevant facilities and landscape elements with GI, including

Table 1: GI indicator system in the research

Category	Sub-category	Indicator	Definition of indicators
External environment	Demographic	Population density (persons/hm^2)	The number of people living on a unit area of land in the grid cell (Refs. [56][60][61])
		Housing density	The ratio of the total residential area to the area of the grid cell (Refs. [56][61])
	Economic	Housing price (CNY)	The average price of all housings in the grid cell (Ref. [56])
		Land use mix (LM)	$LM = -\frac{\left(\sum_{i=1}^{n} P_i \ln P_i\right)}{\ln n}$ P_i is percentage of the area of land use type i in the grid cell to the total area of the grid cell, n is the number of land use types within the grid cell (Ref. [61])
	Environmental	Average daily temperature (℃)	The average value of all the daily mean temperature corresponding to the date of each walking trajectory (Ref. [62])
		Average daily precipitation (mm)	The mean value of all the daily mean precipitation corresponding to the date of each walking trajectory (Ref. [62])
Internal environment	Service facility	Public toilet density (pcs/hm^2)	The ratio of the total number of public toilets to the area of the grid cell (Ref. [63])
		Parking lot density (pcs/hm^2)	The ratio of the total number of parking lots to the area of the grid cell (Ref. [64])
		Urban plaza density (pcs/hm^2)	The ratio of the total number of urban plazas to the area of the grid cell (Ref. [65])
		Bus stop density (pcs/hm^2)	The ratio of the total number of bus stops to the area of the grid cell (Ref. [66])
	Activity route	Number of path crossing (pcs/hm^2)	The total number of path crossings in the grid cell (Ref. [67])
		Path density (km/hm^2)	The ratio of the total length of paths to the area of the grid cell (Ref. [68])
	Water body	Percentage of water body area	The ratio of the total area of water bodies to the total area of the grid cell (Ref. [69])
		Distance to water body (m)	The straight-line distance between the grid cell and the nearest water body (Ref. [69])
	Green space	Normalized Difference Vegetation Index (NDVI)	$NDVI = \frac{(\rho NIR - \rho RED)}{(\rho NIR + \rho RED)}$ *NIR* is the reflected value of near-infrared band, and *RED* is the reflected value of red light band, the result indicates the degree of vegetation cover (Ref. [70])
		Percentage of green space	The ratio of the total area of green spaces and urban parks to the area of the grid cell (Refs. [70][71])

Continued

Table 1: GI indicator system in the research

Category	Sub-category	Indicator	Definition of indicators
Landscape pattern	Number of landscape patches	Patch density (PD)	$PD = \frac{n_i}{A_i}$ n_i is the number of patches in landscape type *i*, A_i is the area of landscape type *i* within the grid cell (Refs. [72][73])
		Large patch index (LPI)	$LPI = \frac{\max_{j=1} a_{ij}}{A}$ A is the total area of the grid cell, a_{ij} is the area of patch *j* in landscape type *i* within the grid cell (Refs. [72][73])
	Landscape shape	Landscape shape index (LSI)	$LSI = \frac{0.25E}{\sqrt{A}}$ A is the total area of the grid cell, E is the total perimeter of all the patches within the grid cell (Refs. [72][73])
		Edge density (ED)	$ED = \frac{E}{A}$ A is the total area of the grid cell, E is the total perimeter of all the patches within the grid cell (Ref. [72])
	Inter-connection between landscape patches	Aggregation index (AI)	$AI = \left[\frac{g_{ij}}{\max g_{ij}}\right] \times 100$ g_{ij} is the number of adjacent pixels around patch *j* in landscape type *i* (Refs. [72][73])
		Division index (DIVISION)	$DIVISION = \left[1 - \sum_{j=1}^{n}\left(\frac{{a_{ij}}^2}{A}\right)\right]$ A is the area of the grid cell, a_{ij} is the area of patch *j* in landscape type *i* (Ref. [74])
		Contagion index (CONTAG)	$CONTAG = \left[1 + \frac{\sum_{i=1}^{m}\sum_{k=1}^{n}\left[P_i\left(\frac{g_{ik}}{\sum_{k=1}^{n} g_{ik}}\right)\right] \times \left[\ln P_i \frac{g_{ik}}{\sum_{k=1}^{n} g_{ik}}\right]}{2\ln m}\right] \times 100\%$ P_i is percentage of the area of land use type *i* in the grid cell to the total area of the grid cell, g_{ij} is the number of adjacent pixels around patch *j* in landscape type *i* (Refs. [72][73])

service facilities, activity routes, water bodies, and green spaces. Landscape pattern indicators include the number of landscape patches, landscape shape, and inter-connection between landscape patches[59]. The walking physical activity indicator system (Table 2) includes frequency and intensity indicators as the dependent variables of the regression models[58][75].

2.3.4 Calculation and Data Preprocessing

Data from each indicator were converted to raster data in ArcGIS (30 m × 30 m pixels), and then went through data processing in Fragstats 4.0 using moving window command (100 m × 100 m window). After importing into ArcGIS, the mean of each indicator in each grid cell was generated with the raster data.

In this study, the *Z*-Scores method was used to standardize the calculated means of all independent variables for each grid cell[76] using the following equation:

$$Z_i = \left(X_i - \mu\right)/S \,, \quad (1)$$

where Z_i is the standardized data, X_i is the value of particular indicator in each grid cell, μ is the mean value of the indicator in the study area, and S is the standard deviation of the indicator.

For the significance and validity tests of the predictive model, a multicollinearity test was performed for the 23 indicators with variance inflation factor (VIF). Four independent variables (patch density, edge density, division index, and contagion index) with significant collinearity (VIF > 5) were excluded from further analysis.

2.3.5 Multiple Linear Regression Model

This paper applied the multiple linear regression model for variance analysis, which is a common statistical model that uses multiple independent variables to explain changes in the dependent variable[77], and is formulated as follows:

$$Y_n = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_m X_m + \varepsilon \,, \quad (2)$$

where Y_n is the dependent variable, i.e. the frequency (Y_1) and intensity (Y_2) of walking physical activity; X_1... X_m are independent variables, i.e. the 19 GI indicators in the urban agglomeration; β_1... β_m are regression coefficients; and ε is random error. The multiple linear regression model was used to examine how the external environment, internal environment, and spatial pattern indicators were related to the frequency and intensity of walking physical activities in the study area.

3 Research Results

3.1 Spatial Analysis of GI and Walking Physical Activity in CZX Urban Agglomeration

Functional analysis and spatial identification of GI in the CZX urban agglomeration delineated 9 forms of GI with a total area of about 553 km^2, accounting for 44% of the total area of the study area. The hubs (Fig. 3) include green hearts and large urban parks in the urban agglomeration. The green heart with an area of about 141.6 km^2 was defined according to the *Regional Planning of Changsha–Zhuzhou–Xiangtan Urban Agglomeration (2008–2020)* and the established ecological protection area. Based on the planning documents of each city[43]~[45] and the indicators studied in relative studies of the structure of Maryland's GI[48] and the GI system of Changsha[49], the urban parks with an area of 100 hm^2 or more were selected. The Xiangjiang River landscape belt, Furong Avenue green belt(the main road connecting Changsha City and Xiangtan City), and the other pedestrian green belt along the major,

Table 2: Walking physical activity indicator system in the research

Indicator	Meaning (Refs. [58][75])
Frequency of walking physical activity	The times of residents' walking physical activities during the study period, i.e. the total count (pcs) of all walking trajectories within the grid cell
Intensity of walking physical activity	The distance of residents' walking physical activities during a single time, i.e. the total length (km) of all walking trajectories within the grid cell

secondary, and branch roads were identified as the links (Fig. 4) based on the distribution analysis of the linear green spaces and paths in the CZX urban agglomeration and the connections between the nodes. The total area of links was 281 km^2. The sites (Fig. 5) mainly consisted of other GI around hubs and links such as city squares, small urban parks, community parks, and other urban green spaces.

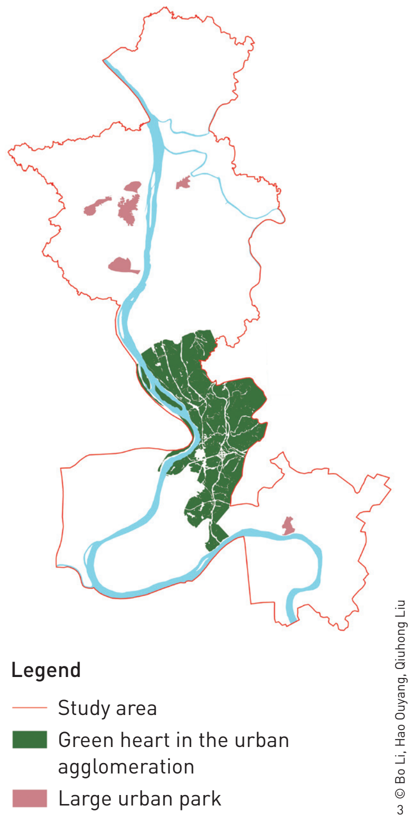
The distribution map of GI in the urban agglomeration was overlaid with the walking trajectories using ArcGIS (Fig. 6), and it showed that 88.3% of the walking trajectories occurred within GI and aggregated in the urban green belts, green spaces, and parks in the central areas of the three cities. In terms of spatial structure (Table 3), links had the largest number and longest total length of the walks, while the hubs had the smallest number and shortest length. As for the types of GI, the other green belts and the other urban green spaces had a relatively larger number and longer total length of trajectories, while the green heart in the urban agglomeration, and the large urban parks had smaller number and shorter length of the trajectories.

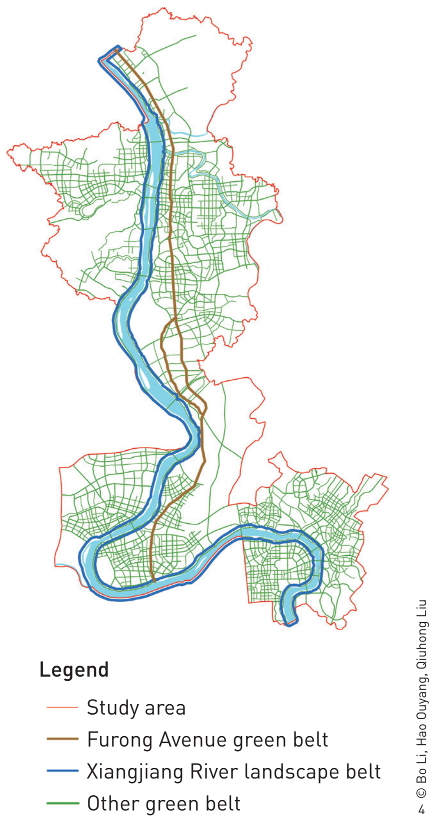
3.2 Correlation Between GI and the Frequency and Intensity of Walking Physical Activities in CZX Urban Agglomeration

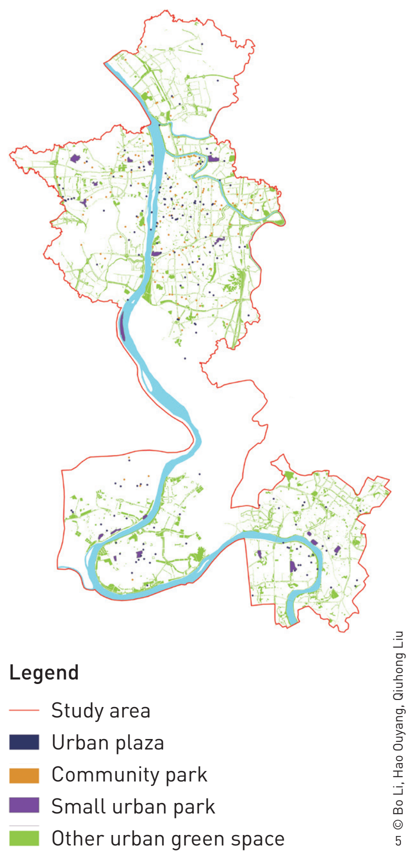
The minimum, maximum, and average values of each indicator were calculated within the 1,436 grid cells (Table 4), and the regression analysis with the standardized data in SPSS are shown in Tables 5 and 6.

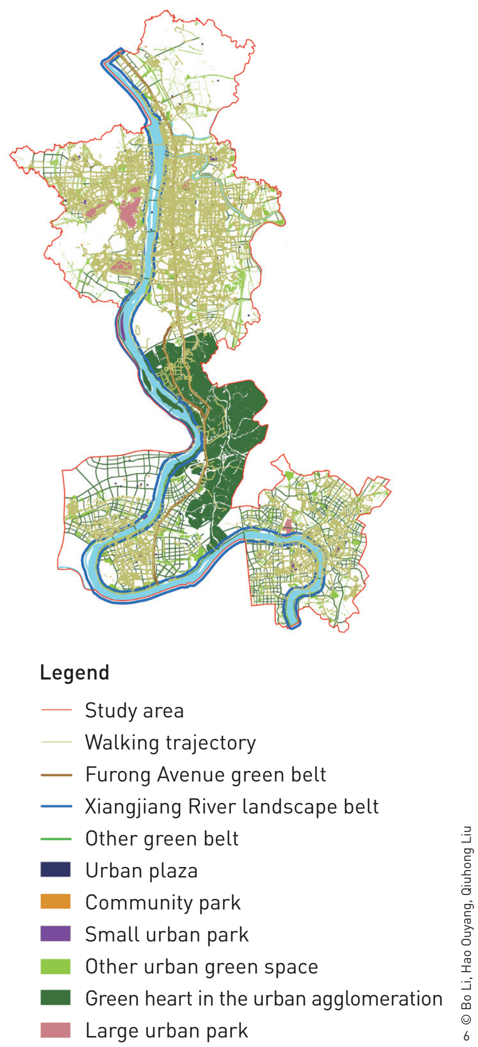
Based on the multiple regression analysis (Table 5), R^2 of the two models are 0.494 and 0.525, respectively, which means that the GI indicators in urban agglomeration as independent variables can explain 49.4% and 52.5% of the changes in walking activities. The amounts of significant F change for both models are less than 0.05, indicating that the multiple linear regression models fit well and the constructed GI indicator system significantly influence the frequency and intensity of walking physical activities. The results of multicollinearity diagnosis (Table 6) show that all the independent variables have VIF less than 5, indicating that there is no multicollinearity and the significance test of the regression model is valid.

GI indicators that were significantly correlated with both frequency and intensity of walking physical activities ($P \leq 0.05$) are









3. Distribution of hubs in CZX urban agglomeration
4. Distribution of links in CZX urban agglomeration
5. Distribution of sites in CZX urban agglomeration
6. Overlay of GI distribution and walking trajectories in CZX urban agglomeration

Table 3: Statistics on GI elements in the urban agglomeration and the number and length of walking trajectories

GI elements	Forms of GI	Total area (km^2)	Number of walking trajectories (pcs)	Length of walking trajectories (km)
Hubs	Green heart in the urban agglomeration	141.60	1,458	342.96
	Large urban park	15.70	8,625	1,264.56
Links	Xiangjiang River landscape belt	68.70	12,643	2,081.22
	Furong Avenue green belt	7.80	11,211	1,705.23
	Other green belt	205.40	71,526	12,157.92
Sites	Urban plaza	5.14	20,021	3,049.83
	Small urban park	4.50	11,794	1,709.15
	Community park	8.05	15,977	2,803.56
	Other urban green space	96.70	64,994	11,162.17

housing density, housing price, public toilet density, urban plaza density, bus stop density, percentage of green spaces, landscape patch index (LPI), and aggregation index (AI). Among them, the public toilet density (standardized coefficient $\beta = -0.080$, $\beta = -0.130$) and LPI ($\beta = -0.051$, $\beta = -0.053$) are negatively related to the frequency and intensity of walking physical activities. GI indicators that had no significant influence on the frequency or intensity of walking physical activities ($P > 0.05$) are population density, average daily precipitation, distance to water body, NDVI, and landscape shape index (LSI).

In addition, the research found that GI indicators differentially influenced the frequency and intensity of walking physical activities. Among external environmental indicators, land use mix (LM) ($P = 0.001$, $\beta = 0.071$) and average daily temperature ($P = 0.006$, $\beta = 0.053$) have a significant positive correlation with intensity, while their correlation with frequency is not significant; among internal environmental indicators, path density ($P = 0.001$, $\beta = 0.134$) has a significant positive correlation with frequency, while percentage of water body area ($P = 0.034$, $\beta = -0.045$) has a significant negative correlation with intensity.

In general, housing density, housing price, and path density have the most significant correlation with the frequency of walking physical activity ($P \leq 0.01$), while housing density, housing price, LM, average daily temperature, public toilet density, urban plaza density, bus stop density, number of path crossing, percentage of green space, and AI have the most significant correlation with the intensity of walking physical activity ($P \leq 0.01$).

4 Discussion

The results confirm that GI in CZX urban agglomeration serves as the primary places for residents' walking physical activity and has a significant correlation with it, which aligns with the results of previous studies[19][39]. It is also verified that the GI factors of external environment, internal environment, and spatial pattern have varied correlations with the frequency and intensity of walking physical activities.

4.1 Spatial Distribution of GI and Walking Physical Activities in CZX Urban Agglomeration

In terms of specific spatial types, walking physical activities mainly took place in links and sites, especially in the other green belts and other urban green spaces, indicating that residents prefer

Table 4: Statistics on each indicator in the research

Indicator	Minimum value	Maximum value	Average value
Population density (persons/hm^2)	0.0000	16,987.2000	2,606.4834
Housing density	0.0000	0.7938	0.1807
Housing price (CNY)	0.0000	29,208.0000	8,372.3174
LM	0.0000	1.0000	0.5826
Average daily temperature (℃)	2.4185	31.8022	21.2389
Average daily precipitation (mm)	0.0000	42.7036	4.3105
Public toilet density (pcs/hm^2)	0.0000	0.4748	0.2433
Parking lot density (pcs/hm^2)	0.0000	27.6562	16.3867
Urban plaza density (pcs/hm^2)	0.0000	0.7787	0.1657
Bus stop density (pcs/hm^2)	0.0000	5.6377	0.8734
Number of path crossing (pcs/hm^2)	0.0000	44.0000	3.5623
Path density (km/hm^2)	0.0000	0.2520	0.0330
Percentage of water body area	0.0000	0.9607	0.1171
Distance to water body (m)	0.0000	5,500.0000	1,008.7858
NDVI	0.0000	0.7757	0.0758
Percentage of green space	0.0000	1.0000	0.1221
LPI	63.2479	100.0000	91.8660
LSI	1.0000	1.3077	1.0740
AI	92.3077	100.0000	98.3069
Frequency of walking physical activity (pcs)	1.0000	819.0000	53.2710
Intensity of walking physical activity (km)	0.0301	74.7600	9.1129

walking along linear spaces (e.g., green belt) or in smaller urban open spaces, which is consistent with existing research findings[78][79]. links can effectively connect different kinds of urban open spaces, e.g., exercise places for walking, urban recreational nodes, and natural scenic areas, and are suitable for walking by meeting various needs for workout and recreation[80]. Enjoying proximity to residential areas and commuting routes, sites can offer amenities and diverse routes for physical exercise and, enhance walking experience, thereby, becoming the main venues for people's daily walking physical activities.

In addition, only a small part of walking trajectories were distributed in green hearts in the urban agglomeration (e.g. Yuelu Mountain, Shiyan Lake) and large urban parks, which may be related to the location and accessibility of hubs. Due to conservation regulations and policies, green hearts and large urban parks rarely locate in highly developed central urban areas, but more in the suburban and rural areas, which requires a longer travel time for residents living in the central districts; and these places often have less recreational or exercise facilities.

4.2 The Impact of GI on the Frequency and Intensity of Walking Physical Activities in CZX Urban Agglomeration

Regarding external environment indicators, the regression analysis shows that housing density (P = 0.000, β = 0.161; P = 0.000, β = 0.186) and housing price (P = 0.006, β = 0.065; P = 0.001, β = 0.075) are positively correlated with the frequency and intensity of walking physical activities. At present, there are few studies directly probing into the correlation between housing prices and walking physical activities, and the findings of this paper need to be verified with empirical research in the future. Meanwhile, relevant research results show that the areas with higher housing density may have a larger number of population and higher travelling demands[81] with higher street connectivity and accessibility for walking[82]. Second, LM has a positive correlation with intensity (P = 0.001, β = 0.071). Areas with higher degree of LM are often equipped with more service facilities and amenities allowing residents to do other things conveniently via walking[83], thus increasing their willingness to walk. Average daily temperature has positive correlations with intensity (P = 0.006, β = 0.053). The walking trajectories were mainly recorded in spring and autumn, when the outdoor temperature is comfortable for physical activities, facilitating people's exercises with a longer duration and higher intensity[84].

As for internal environment indicators, urban plaza density (P = 0.000, β = 0.333; P = 0.000, β = 0.488) and bus stop

Table 5: Multiple regression analysis results of GI on frequency and intensity of walking physical activities in the urban agglomeration

Multiple regression analysis of GI on frequency of walking physical activities in the urban agglomeration						
Model	R	R^2	Adjusted R^2	Errors in standard estimation	R^2 change amount	Significance F amount of change
1	0.703	0.494	0.485	1.225	0.494	0.000
Multiple regression analysis of GI on intensity of walking physical activities in the urban agglomeration						
Model	R	R^2	Adjusted R^2	Errors in standard estimation	R^2 change amount	Significance F amount of change
2	0.725	0.525	0.518	1.158	0.525	0.000

density (P = 0.000, β = 0.220; P = 0.000, β = 0.159) in CZX urban agglomeration are positively correlated with both frequency and intensity of walking physical activities, which suggests that the appropriate increase of the numbers of urban plaza and bus stop to improve the accessibility of infrastructure can promote walking physical activities. Public toilet density is negatively correlated with the frequency (P = 0.016, β = –0.080) and intensity (P = 0.000, β = –0.130) , which is inconsistent with related previous studies, such as Qiang Ma et al. found that the density of public toilets is positively correlated with travel vitality index in commercial area, green spaces and transportation function areas[85]. A possible reason of the disparity of research findings is that the research subjects in Ma's study include all the travel modes, while only walking physical activities is discussed in this paper. Further targeted research is needed to verify the relationship between the distribution of public toilets and walking. In terms of activity route, path density has a positive correlation with frequency (P = 0.001, β = 0.134), while the number of path crossing has a positive correlation with intensity (P = 0.000, β = 0.137), which proves the findings of Peng Zhang et al. and Ken R. Smith et al.[86][87]. These two indicators reflect the level of connectivity within a given area. An improved connectivity implies an easier pedestrian movement between areas—for both walkers and crowds[88]—that enlarges the scope for exercises; also, path crossings can effectively decrease vehicle speed and contribute to a safer walking environment. The percentage of water body area has a negative correlation with the intensity (P = 0.034, β = –0.045), which aligns with the research by Zhiyong Wang et al.[62], but differs from the findings of Marijke Jansen et al. and Camille Perchoux et al.[89][90]. Their studies suggest that adults incline to conduct physical activities around the water bodies near home, combining with their routine activities such as commuting. The reason for the discrepancy among these studies may be the different types of water bodies studied. In Jansen's research, the water bodies were small lakes and ponds in residential areas, which can provide facilities that improve people's access and interaction with water. In contrast, the water bodies in GI of the CZX urban agglomeration are mainly large rivers, lakes or water conservation areas (e.g., Shiyan Lake, Songya Lake) where some public activities are constrained for ecological and water source conservation.

Among spatial pattern indicators, LPI has a negative correlation with the frequency (P = 0.050, β = –0.051) and intensity (P = 0.039, β = –0.053) of walking physical activities, while AI has a positive correlation with frequency (P = 0.023, β = 0.061) and intensity (P = 0.005, β = 0.053). It suggests that the larger area a GI patch has, the lower walking frequency and intensity happened within; while a higher aggregation level GI patches have, the higher walking frequency and intensity are found. The large GI patches in CZX urban agglomeration include green heart and conservation areas such as Yuelu Mountain and Yanghu Wetland Park, which are located in suburban areas with poor accessibility and human activities are partly restricted according to ecological preservation regulations. The aggregated GI patches in the urban agglomeration would strengthen the connectivity among different types of landscape, improve walking experience, and allow walkers to have more options of routes and venues, thus encouraging residents'

Table 6: VIF values, correlation *P* values, and standardized coefficient *β* values of multiple regression model results

Category	Indicator	VIF	GI and frequency of walking physical activities		GI and intensity of walking physical activities	
			Relevance (*P*)	Standardization factor (*β*)	Relevance (*P*)	Standardization factor (*β*)
External environment	Population density	1.123	0.948	0.001	0.173	0.027
	Housing density	1.604	0.000*	0.161	0.000*	0.186
	Housing price	1.472	0.006*	0.065	0.001*	0.075
	LM	1.218	0.206	0.027	0.001*	0.071
	Average daily temperature	1.066	0.951	0.001	0.006*	0.053
	Average daily precipitation	1.061	0.661	0.009	0.709	0.007
Internal environment	Public toilet density	2.958	0.016*	–0.080	0.000*	–0.130
	Parking lot density	2.502	0.232	0.037	0.953	0.002
	Urban plaza density	3.908	0.000*	0.333	0.000*	0.488
	Bus stop density	4.708	0.000*	0.220	0.000*	0.159
	Number of path crossing	4.321	0.348	0.038	0.000*	0.137
	Path density	4.444	0.001*	0.134	0.097	–0.066
	Percentage of water body area	1.274	0.279	–0.024	0.034*	–0.045
	Distance to water body	1.027	0.955	–0.001	0.724	0.007
	NDVI	1.319	0.236	0.026	0.134	0.032
	Percentage of green space	1.237	0.000*	0.105	0.000*	0.107
Spatial pattern	LPI	1.889	0.050*	–0.051	0.039*	–0.053
	LSI	1.008	0.973	0.001	0.197	–0.024
	AI	1.876	0.023*	0.061	0.005*	0.053

NOTE
* means $P \leq 0.05$.

walking physical activities.

The impacts of each indicator category on the frequency and intensity of walking physical activities vary. Spatial pattern indicators have more significant correlations with frequency, while external environment and internal environment indicators have more significant correlations with intensity. This suggests that the spatial structure of landscapes and inter-connection between GI in the urban agglomeration are directly related to the frequency of walking physical activities. Frequency represents residents' intention to conduct regular walking physical activities. A GI patch that has a better connectivity and a higher degree of aggregation usually witnesses a more orderly and stable landscape system, which can properly direct and ease people's movement and provide favorable environment for walking. Intensity implies the duration and physical state of walking. Mixed land use and infrastructure types, as well as suitable temperature and precipitation, help with the creation of diverse landscapes along the long-distance walking routes, alleviate the feelings of exhaustion, and improve the experience of high-intensity walking activities. As the studies by Jelle Van Cauwenberg et al.[91] and Amy Spring et al.[92] reveal, the neighborhoods with convenient transportation and higher accessibility of supportive services can encourage longer-time physical activities.

5 Conclusions

Based on relevant GI theories, this paper identified the GI system in CZX urban agglomeration, and revealed the spatial distribution of walking physical activities and how the GI indicators were correlated with the frequency and intensity of walking physical activities differently through multiple regression model analysis of walking trajectories. The main findings are as follows.

1) The GI in CZX urban agglomeration can be categorized as hubs (i.e. green heart in the urban agglomeration and large urban parks), links (i.e. Xiangjiang River landscape belt, Furong Avenue green belt, and other green belt), and sites (i.e. small urban park, community park, urban plaza, and other urban green space). Walking trajectories were mostly overlapped with links (other green belt) and sites (other urban green space), but less distributed in hubs.

2) Part of the GI indicators have significant correlations with the frequency and intensity of walking physical activities, including housing density and housing price, public toilet density, urban plaza density, bus stop density, percentage of green space, LPI, and AI. Indicators that have not shown significant correlations with the frequency and intensity include population density, average daily precipitation, distance to water body, NDVI, and LSI. In addition, the research proves that the impacts of some indicators on the frequency and intensity vary: LM and average daily temperature have positive correlations with intensity, the percentage of water body area has a negative correlation with intensity, but none of them show significant correlations with frequency; path density has a positive correlation with frequency, but shows no significant correlation with intensity.

The construction of GI that are suitable for walking in urban agglomerations will be beneficial to promoting walking physical activities, developing healthy cities, and enhancing human well-beings. Based on the findings, the research team proposed three strategies for GI construction. Regarding external environment, the construction of multi-functional residential areas with parks, green belt pathways, and other urban green spaces in their surroundings would enhance the overall intensity of residents' walking physical activities. In terms of internal environment, it is important to increase the number of urban plazas and bus stops in GI, build more clustered pedestrian networks, and appropriately add more path crossing to boost people's frequency of walking physical activities. As for landscape pattern, a proper control of the area of large green spaces under the premise of ensuring ecological functions, the increase of number and area of walkable medium and small green spaces, and rational planning of the network of links between various types of GI can ensure the continuity of walking, further enhancing the willingness of the public to walk as physical exercise.

Limited by the data collection, there are some shortcomings in this study. First, since DuoRui is mainly used by the young and the middle-aged, the research findings less reflect how the GI system in CZX agglomeration impacts on the minors' and elderly people's walking physical activities. In the future, target research on these two user groups is expected. Second, this study only used environmental factors as independent variables to examine the relationships between GI and walking physical activities, lacking exploration on the influence mechanism of residents' environmental perception and feelings. Further studies can be conducted to refine the research outcome.

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https://doi.org/10.15302/J-LAF-1-020075 中图分类号 | TU982.2, TU985.1 文献标识码 | A

中国长株潭城市群绿色基础设施对步行体力活动的影响机制研究

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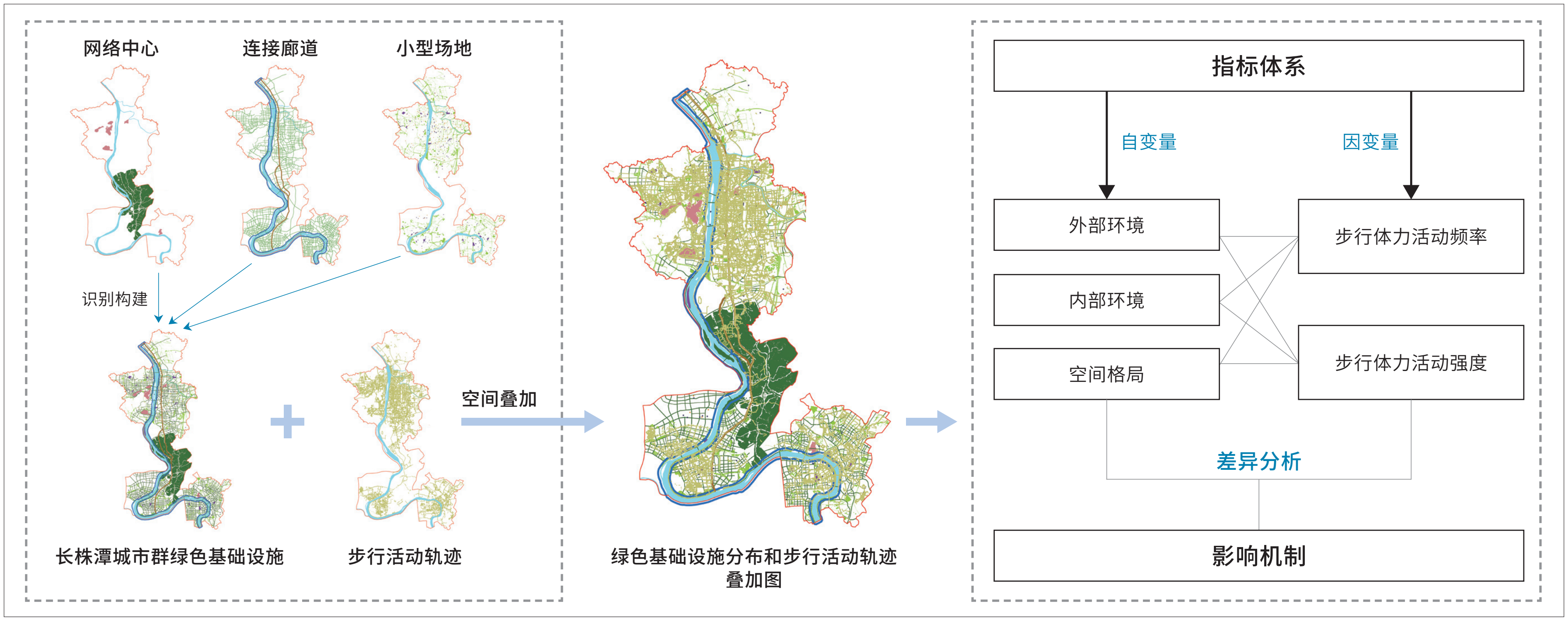
图文摘要



文章亮点

- 长株潭城市群绿色基础设施中步行活动轨迹主要分布在连接廊道和小型场地
- 绿色基础设施内部环境、外部环境与空间格局对居民步行体力活动的影响存在差异
- 提出城市群绿色基础设施的建设及更新策略

关键词

绿色基础设施；
步行体力活动；
影响机制；
长株潭城市群；
空间格局

摘要

步行体力活动可以改善居民健康，探索绿色基础设施对步行体力活动的影响机制是建设健康城市环境的重要一环。本文以中国长株潭城市群绿色基础设施与居民步行体力活动的频率和强度为研究对象，通过识别城市群绿色基础设施的构成要素，分析步行体力活动的空间分布特征；进而构建城市群绿色基础设施指标体系，

运用多元线性回归模型分析城市群绿色基础设施对居民步行体力活动频率和强度的影响机制。研究发现，长株潭城市群居民的步行体力活动轨迹主要分布在绿色基础设施的连接廊道和小型场地中。绿色基础设施的内部环境、外部环境与空间格局均对居民步行体力活动的影响存在差异。其中，外部环境指标中的居住密度、房价水平，内部环境指标中的公共厕所密度、城市广场密度、公交站点密度、绿地面积占比，以及空间格局指标中的最大斑块面积和斑块聚合度指数均与步行体力活动的频率和强度有显著相关性；外部环境指标中的土地利用混合度、日平均气温和内部环境指标中的水体面积占比仅与步行体力活动的强度有显著相关性，内部环境指标中的步道密度仅与步行体力活动的频率有显著相关性。最后，本文分别从外部环境、内部环境和空间格局三个方面提出城市群绿色基础设施的建设及更新策略，以期改善居民步行体力活动环境，充分发挥城市群绿色基础设施的生态和社会价值。

收稿时间

2023-04-21

编辑
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1 引言

随着城市的快速发展，全球范围内许多慢性病的发病率呈上升趋势，目前中国的慢性病患者已超过2亿，占总人口的20%以上[1]。据世界卫生组织2014年统计数据显示，慢性病每年导致全球约4 000万人死亡，占死亡总人数的70%；预计到2030年，每年因慢性病死亡的人数将增至5 500万人[2]。步行体力活动是降低慢性疾病发生率、改善居民健康和提高生活质量的重要途经之一[3]~[5]。现有研究证明，步行运动所处的环境条件能通过影响步行体力活动的频率和强度等因素，进而影响居民的BMI指数和身心健康[6]~[12]。

绿色基础设施（green infrastructure，以下简称GI）是一种由自然区域和其他开放空间组成的相互连接的网络及其附带的工程设施[13][14]。GI的构成要素为网络中心、连接廊道和小型场地[15][16]。GI具有网络化、系统化和高可达性等特征，能够为居民提供低成本亲近自然的户外运动场所和游憩空间[17]，是可供步行体力活动的主要场所[18]。2016年美国国家游憩与公园协会的公园和游憩设施使用情况调查显示，约有52%的受访者表示更倾向于选择公园、城市广场等GI场所进行日常体力活动[19]。

当前对GI与体力活动之间关系的研究主要探讨不同类型GI（如城市绿地和水体）的景观特征（如可达性[20][21]、基础设施的数量和类型[22]、步道网络设计[23]等）对步行体力活动单一属性的影响。例如，克里斯托弗·库茨等人研究发现绿色空间数量的增加将对居民进行体力活动的意愿产生积极影响[24]；李甫忠等人研究发现住房密度及绿色和开放休闲空间、十字路口数量的增加可以增强人们持续步行的意愿等[25]；阿卜杜拉·阿克比纳等人、贾斯珀·希佩里恩等人发现步行体力活动的频率会随着与GI之间距离的增加而显著降低[26][27]；托马斯·阿斯特尔–伯特等人和克里斯托弗·库茨等人发现，随着居住范围内GI数量的增加和距离的缩短，成年人每周进行不同强度体力活动的频率均会显著提升[22][24]。现有对GI体系的系统性研究则侧重于GI空间格局对人类生产、生活活动产生的影响[28]，以及其与人居环境质量和人类健康水平的关联性分析[29]，较少探讨其对步行体力活动的影响。总的来说，相关研究还需探索GI整体格局与步行体力活动的相关性，以及进一步综合分析GI对运动频率和强度的影响差异和影响机制。

城市群是指“以1~2个特大型城市为核心，包括周围若干个城市所组成的内部具有垂直的和横向的经济联系，并具有发达的一体化管理的基础设施系统给以支撑的经济区域”[30]。相关报告显示，中国城市群中的常住人口已占全国总人口的64.6%[31]，由此可见，城市群GI将是保障大部分城乡居民进行步行体力活动的基本设施。当前城市群GI的研究集中于城市群绿地系统建设[32]~[34]、城市群绿心保护性开发[35]、景观安全格局构建[36]和绿色空间评价[37][38]等。众多研究表明，城市群GI能够通过改变生态用地格局来提升生态效益、改善人居环境品质，同时满足各类人群的不同运动需求，促进居民步行体力活动和社会交往，提升公众健康水平[33][39]~[41]。

为了进一步理解城市群GI和步行体力活动之前的关系，本文对中国长株潭城市群GI和居民步行体力活动展开研究。通过构建多元线性回归模型进行差异分析，探索城市群GI对步行体力活动频率和强度的影响机制，并制定有利于促进居民步行运动和健康城市环境建设的策略，以期提升城市居民福祉。

2 研究方法

2.1 研究区域

本文研究区域为湖南省长株潭城市群（长沙市、株洲市、湘潭市）的中心城区，包括长沙市的天心区、芙蓉区、开福区、雨花区和岳麓区；株洲市的天元区、芦淞区、石峰区和荷塘区；以及湘潭市的岳塘区和雨湖区，总面积约为1 260.65km^2（图1）①。2021年长株潭城市群常住人口为1 683.16万人，城镇化率为77.70%，是湖南省经济发展的核心增长极[42]。

2.2 数据来源

研究所用的步行体力活动数据来源于“多锐运动”APP上记录的2016~2019年的运动数据。这款APP是一家运动健康移动互联网公司旗下的应用程序，主要用户群体为青年人和中年人②，在数据采集期间，研究区域的用户量为3 785人。该APP能够通过精准算法结合智能硬件进行运动检测、数据分析，生成专业测评报告，从而定制专业而有针对性的运动计划。所获取的原始数据包括跑步和步行轨迹数据，其中步行数据量约占83%，本研究仅筛选步行数据作为研究对象。采集到的步行轨迹数据的内容包含空间位置、运动类型、运动时长、运动距离、运动日期和运动频率等信息。

本研究中的城市用地分类数据采用《长沙市城市总体规划2003—2020（2014年修订）》《湘潭市城市总体规划2010—2020（2017年修订）》《株洲市城市总体规划（2006—2020年）（2017年修订）》[43]~[45]，通过栅格矢量化，并根据2020年实际建设情况进行调整和修正。路网数据基于由“开放街道地图”获取到的数据进行分类处理，并根据实际建设情况进行调整和修正③。2016~2020年日平均降水和日平均气温数据来源于国家气象信息中心。归一化植被指数（NDVI）数据来源于USGS网站2019年12月Landsat 8数据，经计算得出研究区域内的NDVI数值。房价数据通过获取安居客、链家和房天下三个房地产平台2016~2019年的月度数据，并进行去重处理后计算平均值得出。人口数据来源于第七次全国人口普查统计数据（湖南省统计局），包括研究区域内各个街道的人口总数，同时依据获取到的房价数据中带有的户数信息，统计出各小区的人口数量，并根据街道人口数据进行修正。最终，通过高德地图爬取2019年12月的各类POI数据（如公交站点、公共厕所、城市广场和公园等），并进行纠偏与清洗。

① 研究区域总面积参考湖南省人民政府官网计算得出。

② 主要用户群信息来源于多锐运动团队。

③ 运用高德地图将城市总体规划中的土地利用分类、开放街道地图中的路网信息和 2020 年的城市用地、路网、基础设施的实际建设情况进行人工比对，并对矢量数据进行修正。

2.3 分析方法

2.3.1 城市群GI的划定

已被广泛认可和应用的GI范围的划定方法一般包括确定GI的目标和定位，确定其构成要素（即网络中心、连接廊道和小型场地[15][16]），以及识别网络格局三个步骤[46]。

网络中心是指较少受到外界干扰、面积较大的自然栖息地斑块，包括处于原生状态的土地、生态保护区、郊野公园、森林、湖泊、湿地、农田、牧场和林地等[47]。网络中心的划定需要结合地区发展和保护政策，综合考虑斑块面积大小、物种种类数量，以及在GI格局中的连通性等指标[48]，对比筛选出各项指标均评价较高的，具有较高生态价值的景观斑块作为网络中心[49]。

连接廊道是指线性的、连接网络中心和小型场地的生态廊道，主要包括河流和城市道路周边，以及防护绿带等带状绿地[50]。连接廊道的位置与范围的划定可以基于GIS技术和地面调查获取的生态本底、面积、连通性等多种区域统计数据的集合而得出[51][52]。

小型场地是对网络中心和连接廊道的补充，为人们提供兼具生态和社会价值的休闲场地，主要包括小型城市公园、广场、街旁绿地、社区公园等[47]。在相关研究中，小型场地主要是在划定了网络中心和链接廊道之后进行定性划分[15][16][50]~[52]。本研究中的小型场地主要基于土地利用数据和城市POI数据，通过识别各类与居民生活联系密切的绿地和广场等节点进而筛选得出。

2.3.2 网格单元划分

格网分析已经在景观评价、环境监测、社会分析等方面得到了大量应用[53]~[55]，经过格网划分展示的景观单元可以体现景观的异质性和空间特性，同时有利于后续进行多源数据的融合与分析。本文中格网尺度的选择主要依据10分钟生活圈的范围来判定，通常情况下，人均步行速度为4.60~5.35km/h，10分钟的运动距离大约为800m。参考相关研究[53][54]，通过ArcGIS 10.6的渔网创建工具，对研究区构建800m × 800m的格网体系，并将格网图层与GI图层进行叠加，筛选出1 436个包含城市群GI的网格单元作为研究样本区域（图2）。

2.3.3 指标体系构建

为了更好地表征城市群GI的属性特征、系统性探讨GI与步行体力活动的关系，本文参考相关研究成果[56]~[74]结合研究区现状，从GI的外部环境、内部环境和景观格局三个层面构建GI指标体系（表1），得到分析模型的自变量。外部环境指标包括人口、经济和环境指标，其中人口和经济指标虽然不是GI的构成因素，但是一些现有研究将其作为影响体力活动的自变量而非控制变量参与研究，结果显示了显著的相关性[56]~[58]。内部环境指标指GI内部的基础服务设施和景观要素，包括基础服务设施、

表 1：绿色基础设施指标体系

类别	准则	指标	指标释义
外部环境	人口	人口密度（人 /hm^2）	网格单元内单位面积土地上居住的人口数（参考文献：[56][60][61]）
		居住密度	网格单元内居住用地总面积与网格单元总面积的比值（参考文献：[56][61]）
	经济	房价水平（元）	网格单元内所有住区的平均房价（参考文献：[56]）
		土地利用混合度（LM）	$LM = -\frac{\left(\sum_{i=1}^{n} P_i \ln P_i\right)}{\ln n}$ 式中，P_i 表示在网格单元内各类土地利用中第 i 类用地占网格单元总面积的比重，n 为网格单元内土地利用类型的总数（参考文献：[61]）
	环境	日平均气温（℃）	网格单元内所有运动轨迹数据对应采集当日平均温度的均值（参考文献：[62]）
		日平均降水（mm）	网格单元内所有运动轨迹数据对应采集当日平均降水的均值（参考文献：[62]）
内部环境	基础服务设施	公共厕所密度（个 /hm^2）	网格单元内公共厕所的总数量与该区域面积的比值（参考文献：[63]）
		停车场地密度（个 /hm^2）	网格单元内停车场的总数量与该区域面积的比值（参考文献：[64]）
		城市广场密度（个 /hm^2）	网格单元内城市广场的总数量与该区域面积的比值（参考文献：[65]）
		公交站点密度（个 /hm^2）	网格单元内公交站点的总数量与该区域面积的比值（参考文献：[66]）
	运动路径	步道交叉口数量（个 /hm^2）	网格单元内步行道相交所形成的交叉口数量总和（参考文献：[67]）
		步道密度（km/hm^2）	网格单元内步道的总长度与该区域面积的比值（参考文献：[68]）
	水体	水体面积占比	网格单元内水体的总面积与该区域面积的比值（参考文献：[69]）
		距水体距离（m）	网格单元距离周边最近水体的直线距离（参考文献：[69]）
	绿地	归一化植被指数（NDVI）	$NDVI = \frac{(\rho NIR - \rho RED)}{(\rho NIR + \rho RED)}$ NIR 为近红外波段的反射值，RED 为红光波段的反射值，结果可表示样本区内的植被覆盖程度（参考文献：[70]）
		绿地面积占比	网格单元内绿地和城市公园总面积占该区域面积的比值（参考文献：[70][71]）

续表见下页

表 1：绿色基础设施指标体系

类别	准则	指标	指标释义
空间格局	景观数量	斑块密度（PD）	$\mathrm{PD} = \frac{n_i}{A_i}$ 式中，n_i 为网格单元中景观类型 i 中的斑块数，A_i 为第 i 类景观的面积（参考文献：[72][73]）
		最大斑块面积占比（LPI）	$\mathrm{LPI} = \frac{\max_{j=1} a_{ij}}{A}$ 式中，A 为网格单元的总面积；a_{ij} 为第 i 类景观中斑块 j 的面积（参考文献：[72][73]）
	景观形状	景观形状指数（LSI）	$\mathrm{LSI} = \frac{0.25E}{\sqrt{A}}$ 式中，A 为网格单元的总面积；E 为网格单元内所有斑块边界的总周长（参考文献：[72][73]）
		斑块边缘密度 (ED)	$\mathrm{ED} = \frac{E}{A}$ 式中，E 为网格单元内所有斑块边界的总周长，A 为网格单元的总面积（参考文献：[72]）
	景观斑块间关系	斑块聚合度指数（AI）	$\mathrm{AI} = \left[\frac{g_{ij}}{\max g_{ij}}\right] \times 100$ 式中，g_{ij} 为网格单元中第 i 类景观中斑块 j 的相邻像素数（参考文献：[72][73]）
		斑块分离度指数（DIVISION）	$\mathrm{DIVISION} = \left[1 - \sum_{j=1}^{n}\left(\frac{a_{ij}^{2}}{A}\right)\right]$ 式中，A 为网格单元的总面积；a_{ij} 是第 i 类景观中斑块 j 的面积（参考文献：[74]）
		斑块蔓延度指数（CONTAG）	$\mathrm{CONTAG} = \left[1 + \frac{\sum_{i=1}^{m}\sum_{k=1}^{n}\left[P_i\left(\frac{g_{ik}}{\sum_{k=1}^{n} g_{ik}}\right)\right] \times \left[\ln P_i \frac{g_{ik}}{\sum_{k=1}^{n} g_{ik}}\right]}{2\ln m}\right] \times 100\%$ 式中，P_i 为第 i 类景观占景观总面积的比例；g_{ik} 是第 i 类景观中与景观斑块 k 相邻的像素数（参考文献：[72][73]）

运动路径、水体和绿地指标。空间格局指标包括景观数量、景观形状和景观斑块间关系[59]。步行体力活动指标体系（表2）主要包括步行体力活动的频率和强度[58][75]，是分析模型的因变量。

2.3.4 GI指数计算与数据预处理

将各项指标数据在ArcGIS软件中转换为栅格数据（像素精度为30m），导入Fragstats4.0软件，通过移动窗口（Moving Windows）命令，以100m×100m的方形窗口进行计算，将计算后的栅格数据导入到ArcGIS软件中，分别计算每个网格单元内所有像素各个指标的平均值。

本研究采用Z-Scores法对计算所得网格单元中的平均值进行标准化处理[76]，其公式如下：

$$Z_i = (X_i - \mu)/S \quad (1)$$

其中，Z_i为标准化后的数据，X_i为指标变量在每个网格单元的数值，μ为指标变量在研究区域内的均值，S为指标变量的标准差。

为了保证显著性检验的科学性及预测模型的有效性，运用方差膨胀因子（VIF）对23项指标（表1）进行多重共线性检验，剔除具有显著共线性（VIF>5）的4个自变量（斑块密度、斑块边缘密度、斑块分离度指数和斑块蔓延度指数），最终得到19项自变量指标进行后续分析。

2.3.5 多元线性回归模型

本研究利用多元线性回归模型进行差异分析。多元线性回归模型是用多个自变量解释因变量的变化的一种常用统计模型[77]，其公式为：

$$Y_n = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_m X_m + \varepsilon \quad (2)$$

式中，Y_n为因变量，即步行体力活动频率（Y_1）和强度（Y_2）；$X_1 \ldots X_m$为自变量，即19项城市群GI指标；$\beta_1 \ldots \beta_m$为回归系数；ε为随机误差项。以此构建多元线性回归模型，讨论GI外部环境、内部环境和空间格局指标与步行体力活动频率和强度之间的关系。

3 研究结果

3.1 城市群GI识别与步行体力活动空间分析

通过对长株潭城市群GI的功能分析和空间识别，划定9类GI空间，其总面积约为553km²，占城市群总面积的44%。网络中心（图3）主要包括长株潭城市群绿心和大型城市公园，依据《长株潭城市群区域规划（2008—2020）》及其规定的生态保护范围，划定面积约141.6km²的长株潭绿心；参照长沙市、湘潭市和株洲市的相关规划文件[43]-[45]，以及付喜娥等人对马里兰州GI结构的研究[48]和杨健等人对长沙市GI体系的研究[49]中采用的相关指标，以面积大于100hm²为标准结合相关指标，筛选出总面积为15.7km²的大型城市公园。连接廊道（图4）的识别主要基于长株潭城市群线性绿地和市域步道的分布情况，通过识别各节点之间的连接关系而得出，包括湘江景观带、芙蓉大道（连接长沙市和湘潭市的主干道）绿带，以及城市主、次、支三级道路沿线的其他城市道路绿带，总面积为281.9km²。小型场地（图5）主要由围绕在网络中心和连接廊道周边的其他GI组成，包括小型城市绿地、城市广场、社区公园和小型城市公园。

借助ArcGIS软件将城市群GI分布图与居民步行体力活动轨迹叠加（图6），计算GI内部的轨迹数量与步行体力活动轨迹总数的百分比，结果显示88.3%的步行活动发生在GI内部，且集中分布在三个城市中心城区的城市绿道、绿地和公园等区域。在空间结构上（表3），连接廊道中有最多的步行轨迹数量和最大的轨迹总长，而网络中心拥有最少的步行轨迹数量和最短的长度。从具体类型来看，其他城市道路绿带和其他城市绿地这两类中的轨迹数量和长度均较大，城市群绿心、大型城市公园的轨迹数量和长度均较小。

3.2 城市群GI与步行体力活动频率和强度之间的相关性

通过对1 436个网格单元内的指标进行计算，统计各类指标的最小值、最大值和平均值（表4），并在SPSS软件中对标准化后的数据进行回归分析（表5，6）。

由多元回归分析结果（表5）可见：两个模型结果的R^2分别为0.494

表 2：步行体力活动指标体系

指标	含义（参考文献：[58][75]）
步行体力活动频率	单位时间内居民步行体力活动的次数，以网格单元内所有步行轨迹的数量（个）表示
步行体力活动强度	单次运动过程中居民步行体力活动的距离，以网格单元内所有步行轨迹的总长度（km）表示

表3：城市群GI构成要素及其中步行轨迹数量和长度统计

GI结构	GI类型	总面积（km^2）	步行轨迹数量（个）	步行轨迹长度（km）
网络中心	城市群绿心	141.60	1,458	342.96
	大型城市公园	15.70	8,625	1,264.56
连接廊道	湘江景观带	68.70	12,643	2,081.22
	芙蓉大道绿带	7.80	11,211	1,705.23
	其他城市道路绿带	205.40	71,526	12,157.92
小型场地	城市广场	5.14	20,021	3,049.83
	小型城市公园	4.50	11,794	1,709.15
	社区公园	8.05	15,977	2,803.56
	其他城市绿地	96.70	64,994	11,162.17

和0.525，意味着参与本次研究的城市群GI自变量指标能分别解释步行体力活动频率和强度变化的49.4%和52.5%；两个模型的显著性F变化量均小于0.05，说明多元线性回归模型拟合效果较好，本研究所构建的城市群GI指标体系对步行体力活动频率和强度变化有显著影响。多重共线性诊断（表6）结果显示，所有自变量指标的VIF均小于5，自变量之间不存在多重共线性，回归模型显著性检验成立。

部分城市群GI指标对步行体力活动的频率或强度均表现出显著影响（$P\leqslant0.05$），包括居住密度、房价水平、公共厕所密度、城市广场密度、公交站点密度、绿地公园占比、最大斑块面积占比（LPI）和斑块聚合度指数（AI），其中公共厕所密度（标准化系数$\beta=-0.080$，$\beta=-0.130$）、LPI（$\beta=-0.051$，$\beta=-0.053$）和步行体力活动的频率与强度呈负相关关系。而部分城市群GI指标则对步行体力活动的频率或强度影响均不显著（$P>0.05$），包括人口密度、日平均降水、距水体距离、NDVI和景观形状指数（LSI）。

部分城市群GI指标对步行体力活动的频率或强度的影响存在差异。在外部环境指标中，土地利用混合度（LM）（$P=0.001$，$\beta=0.071$）和日平均气温（$P=0.006$，$\beta=0.053$）和步行体力活动强度具有显著正相关关系，而对步行体力活动频率影响不显著；在内部环境指标中，步道密度（$P=0.001$，$\beta=0.134$）和步行体力活动频率有显著正相关关系，而水体面积占比（$P=0.034$，$\beta=-0.045$）和步行体力活动强度显著负相关。

整体而言，居住密度、房价水平、步道密度对步行体力活动频率的影响最显著（$P\leqslant0.01$），居住密度、房价水平、LM、日平均气温、公共厕所密度、城市广场密度、公交站点密度、步道交叉口数量、绿地面积占比和AI对步行体力活动强度的影响最显著（$P\leqslant0.01$）。

4 讨论

研究结果证实了长株潭城市群GI是居民进行步行体力活动的主要场所，且城市群GI对步行体力活动具有显著影响，这与先前诸多研究结果一致[19][39]。研究结果还从外部环境、内部环境和空间格局指标层面证实了城市群GI对步行体力活动的频率和强度均存在不同的影响。

4.1 城市群GI与步行体力活动空间分布的关系

步行体力活动主要集中在连接廊道和小型场地中，特别是其他城市

表 4：各类型指标数值统计表

指标	最小值	最大值	平均值
人口密度（人 /hm^2）	0.0000	16,987.2000	2,606.4834
居住密度	0.0000	0.7938	0.1807
房价水平（元）	0.0000	29,208.0000	8,372.3174
LM	0.0000	1.0000	0.5826
日平均气温（℃）	2.4185	31.8022	21.2389
日平均降水（mm）	0.0000	42.7036	4.3105
公共厕所密度（个 /hm^2）	0.0000	0.4748	0.2433
停车场地密度（个 /hm^2）	0.0000	27.6562	16.3867
城市广场密度（个 /hm^2）	0.0000	0.7787	0.1657
公交站点密度（个 /hm^2）	0.0000	5.6377	0.8734
步道交叉口数量（个 /hm^2）	0.0000	44.0000	3.5623
步道密度（km/hm^2）	0.0000	0.2520	0.0330
水体面积占比	0.0000	0.9607	0.1171
距水体距离（m）	0.0000	5,500.0000	1,008.7858
NDVI	0.0000	0.7757	0.0758
绿地面积占比	0.0000	1.0000	0.1221
LPI	63.2479	100.0000	91.8660
LSI	1.0000	1.3077	1.0740
AI	92.3077	100.0000	98.3069
步行体力活动频率（个）	1.0000	819.0000	53.2710
步行体力活动强度（km）	0.0301	74.7600	9.1129

道路绿带和其他城市绿地，说明居民更倾向于沿绿道等线性空间或者是在小型城市开放空间中开展步行体力活动，这与现有研究的观点一致[78][79]。连接廊道可以有效连接各类城市开放空间，如步行运动场所、城市游憩节点和自然风景名胜等，适宜的步行尺度使其可以满足健身锻炼和休闲游憩的多种需求[80]。小型场地常见于居住地周边，距离居民通勤路线较近，具备相对完善的基础设施和趣味灵活的游线，从而易于提高居民的步行活动体验，成为居民进行简单步行活动的主要场地。

此外，仅少部分步行体力活动轨迹分布在城市群绿心（如岳麓山、石燕湖等）和大型城市公园中，这可能与网络中心的坐落位置和可达性有关。因自然保护管控政策要求，城市群绿心和大型城市公园较少分布在土地开发强度较大的高密度城市中心区域，而更多分布在市郊、乡村等区域，对于居住在城市中的居民来说，路程中花费的时间较长且游憩设施较少，因而出现在网络中心的步行体力活动较少。

4.2 长株潭城市群GI对步行体力活动频率和强度的影响

从外部环境指标来看，回归分析结果显示城市群GI中居住密度（P=0.000，β=0.161；P=0.000，β=0.186）和房价水平（P=0.006，β=0.065；P=0.001，β=0.075）与步行体力活动的频率和强度呈正相关关系。现有文献中直接论证房价水平影响步行体力活动的研究成果较少，因此本文的相关研究结果有待后续更多案例研究加以验证。而居住密度较高的区域可能人口数量更多，总体出行需求更高[81]，同时，这类区域具有更高的街道连通性、可达性，更易于为居民带来良好的步行运动体验[82]。其次，LM与步行体力活动的强度呈现正相关关系（P=0.001，β=0.071），LM越高的区域往往在步行范围内分布有多种设施，以便于居民在一次步行活动过程中完成多项任务[83]，从而提高步行活动倾向；日平均气温对居民步行体力活动的强度具有显著正向影响（P=0.006，β=0.053），本研究中步行轨迹数据主要集中在春季和秋季，在这两个季节中较高的温度可以提高人体感知舒适度，减少疲惫感，让身体各项机能能够负担更长时间、更高强度的运动[84]。

从内部环境指标中来看，长株潭城市群GI中城市广场（P=0.000，β=0.333；P=0.000，β=0.488）和公交站点密度（P=0.000，β=0.220；P=0.000，β=0.159）与步行体力活动的频率和强度均呈正相关关系，这表明可以通过适当增加城市广场和公交站点来提高基础设施的可达性，从而促进步行体力活动的开展。而公共厕所密度和步行体力活动的频率（P=0.016，β=−0.080）和强度（P=0.000，β=−0.130）均呈负相关关系。这与以往相关研究存在一定的差异，如马强等人研究发现在上海的商业区、绿地和交通功能区，公共厕所密度与出行活力指数呈正相关[85]。导致研究结果不同的原因可能是上述文献的研究对象包含了多种出行方式，而本文只关注于步行体力活动，因而后续需要进一步细分研究继续探讨公共厕所空间配置与步行体力活动之间的关系。运动路径方

面，步道密度和步行活动频率呈正相关关系（P=0.001，β=0.134）；步道交叉口数量和步行活动强度呈正相关关系（P=0.000，β=0.137），这验证了张鹏等人、肯・R・史密斯等人的研究结果[86][87]，步道交叉口数量和步道密度往往代表了一个地区连通性的强弱，更好的连通性不仅易于行走，还能有效疏解聚集性人群[88]，促进居民在不同类型GI中流动，扩大步行体力活动的范围；同时步道交叉口能有效降低道路交通中的机动车车速，提高步行环境的安全性。水体面积占比和步行体力活动的强度呈负相关关系（P=0.034，β=−0.045），这与王志勇等人的研究结果相同[62]，但是与玛丽克・詹森等人和卡密尔・佩尔舒等人的研究结果存在差异[89][90]，他们发现成年人更倾向于使用离住宅更近的水体空间进行体力活动，从而与下班等通勤性、必要性的活动相结合。造成研究结果差异的原因可能在于水体景观的类型不同，詹森等人研究的水体主要以住区周边的小面积湖泊、池塘为主，这里往往会配备较多亲水设施，方便居民与水接触，而长株潭城市群GI中的水体主要为面积较大的江河湖泊或水源涵养区（如长沙石燕湖、松雅湖等），生态保护和水源保护的要求限制了公众的亲水活动，从而在一定程度上限制了步行体力活动。

从景观格局指标来看，LPI与步行体力活动的频率（P=0.050，β=−0.051）和强度（P=0.039，β=−0.053）呈负相关关系，而AI与步行体力活动的频率（P=0.023，β=0.061）和强度（P=0.005，β=0.053）呈正相关关系，说明城市群核心GI斑块面积越大，相应的居民步行活动的频率和强度越低；而斑块间聚合关系越好，越能促进居民步行活动的频率和强度。长株潭GI大型景观斑块主要包括长株潭城市群绿心，以及岳麓山和洋湖湿地公园等大型自然保护区，它们主要位于城郊，远离城市核心区，可达性相对较差，并且因生态保护要求在一定程度上限制步行等人为活动。城市群GI中良好的景观聚合关系则可以在加强各景观类型之间的连通性、保障步行运动通畅和步行运动中的可选择性，从而提高居民进行步行体力活动的意愿。

从城市群GI对频率和强度的影响差异来看，景观格局指标对频率的影响更显著，而外部环境指标和内部环境指标对强度的影响更显著。这表明城市群GI的景观空间结构和内部景观连接关系会直接影响居民步行体力活动的频率，原因可能在于频率代表了居民进行周期性步行体力活动的意向，而连接性更强、聚合度更高的GI斑块通常具有更有序、更稳定的景观系统，能合理分配和疏解不同人群的流动，为步行提供有利的城市群环境。强度表示居民进行步行体力活动持续的时间和运动状态，丰富的土地利用和基础设施类型，以及适宜的环境温度和降水能有效满足居民在长时间、长距离运动中对景观多样化的需求，降低高负荷运动的疲惫感，提升高强度活动的体验感。正如耶勒・范・考文伯格等人和艾米・斯普林研究显示，交通越便利、服务设施可达性越高的街区，越有利于提升居民体力活动时间[91][92]。

5 结论

基于GI相关理论，本研究识别并构建了长株潭城市群GI体系，结合居民步行体力活动轨迹数据，通过构建多元线性回归模型，探讨了在长株潭城市群GI中步行体力活动的空间分布和各项GI指标对步行体力活动频率和强度的影响差异，主要研究结论如下：

1）长株潭城市群GI可分为网络中心（包括城市群绿心和大型城市公园）、连接廊道（包括湘江景观带、芙蓉大道绿带和其他城市道路绿带）、小型场地（包括小型城市公园、社区公园、城市广场和其他城市绿地）。步行轨迹集中分布在连接廊道的城市道路绿带步道中，以及小

表 5：城市群 GI 与步行体力活动频率和强度的多元回归分析结果

城市群 GI 对步行体力活动频率影响的多元回归分析						
模型	R	R^2	调整后 R^2	标准估算的错误	R^2 变化量	显著性 F 变化量
1	0.703	0.494	0.485	1.225	0.494	0.000
城市群 GI 对步行体力活动强度影响的多元回归分析						
模型	R	R^2	调整后 R^2	标准估算的错误	R^2 变化量	显著性 F 变化量
2	0.725	0.525	0.518	1.158	0.525	0.000

表 6：多元回归模型 VIF 值、相关性 P 值和标准化系数 β 值

类别	指标	VIF	城市群 GI 与步行体力活动频率		城市群 GI 与步行体力活动强度	
			相关性（P）	标准化系数（β）	相关性（P）	标准化系数（β）
外部环境	人口密度	1.123	0.948	0.001	0.173	0.027
	居住密度	1.604	0.000*	0.161	0.000*	0.186
	房价水平	1.472	0.006*	0.065	0.001*	0.075
	LM	1.218	0.206	0.027	0.001*	0.071
	日平均气温	1.066	0.951	0.001	0.006*	0.053
	日平均降水	1.061	0.661	0.009	0.709	0.007
内部环境	公共厕所密度	2.958	0.016*	-0.080	0.000*	-0.130
	停车场地密度	2.502	0.232	0.037	0.953	0.002
	城市广场密度	3.908	0.000*	0.333	0.000*	0.488
	公交站点密度	4.708	0.000*	0.220	0.000*	0.159
	步道交叉口数量	4.321	0.348	0.038	0.000*	0.137
	步道密度	4.444	0.001*	0.134	0.097	-0.066
	水体面积占比	1.274	0.279	-0.024	0.034*	-0.045
	距水体距离	1.027	0.955	-0.001	0.724	0.007
	NDVI	1.319	0.236	0.026	0.134	0.032
	绿地面积占比	1.237	0.000*	0.105	0.000*	0.107
景观格局	LPI	1.889	0.050*	-0.051	0.039*	-0.053
	LSI	1.008	0.973	0.001	0.197	-0.024
	AI	1.876	0.023*	0.061	0.005*	0.053

注
* 代表 $P \leqslant 0.05$。

型场地的其他城市绿地中，在网络中心中分布较少。

2）GI外部环境指标中的居住密度和房价水平，内部环境指标中的公共厕所密度、城市广场密度、公交站点密度和绿地面积占比，空间格局指标中的LPI和AI对步行体力活动的频率和强度均有显著影响。人口密度、日平均降水、距水体距离、NDVI和LSI对步行体力活动的频率和强度的影响均未表现出显著的相关性。此外，部分城市群GI指标与步行体力活动的频率和强度的相关性存在差异：LM、日平均气温和步行活动的强度呈显著正相关关系，水体面积占比和步行体力活动的强度呈显著负相关关系，而这些指标都未表现出与频率的显著相关性；步道密度仅对步行运动频率有显著正向影响，而未表现出与强度的显著相关性。

构建适宜步行体力活动的城市群GI，有利于提高居民的步行体力活动水平，营造健康城市，进而提升城市居民福祉。依据本文研究结果，研究团队提出三项城市群GI建设策略。在外部环境方面，打造与公园、步行绿道和其他绿地临近的多业态、功能型住区环境，可以整体增强居民步行体力活动强度。在内部环境方面，增加GI中城市广场、公交站点等设施的数量，构建相对集中的人行步道网络，并适当增加步道交叉口数量，可有效提升居民进行步行体力活动的频率。在空间格局方面，在保障生态功能的前提下适当控制大型绿地面积，增加可步行的中小型绿地面积和数量，合理规划连接各类GI的步行绿道系统，可以保证步行运动过程的连续性，进而全面提升步行体力活动的频率和强度。

受采集到的数据所限，本研究还存在一些不足。首先，多锐APP的主要用户是青年和中年人，因此本文未能体现城市群GI对未成年人和老年人步行体力活动的影响，未来将进一步采集这两类人群的步行体力活动数据开展专项研究。其次，本研究仅使用客观环境要素作为自变量来研究GI与步行体力活动的关系，缺少对居民环境感知、心理感受等主观因素的探讨，后续将进一步拓展这方面的研究。

图 1. 研究区居民步行体力活动轨迹分布
图 2. 网格单元分布图
图 3. 城市群 GI 网络中心分布图
图 4. 城市群 GI 连接廊道分布图
图 5. 城市群 GI 小型场地分布图
图 6. 城市群 GI 与步行轨迹叠加图