Built environments and frailty in older adults: a three-year longitudinal JAGES study

（高齢者における個人・地域レベルの建造環境とフレイル発症の関連 -3 年間の JAGES 縦断研究-）

千葉大学大学院医学薬学府

先進予防医学共同専攻

(主任: 近藤 克則教授)

森 優太

Abstract

Background This study investigated the relationship between built environments and the onset of frailty after 3 years.

Methods This was a longitudinal study using prospective cohort data from the 2013 Japan Gerontological Evaluation Study on 38,829 older adults nested in 562 regions who were not frail. The dependent variable, frailty, was assessed using the Kihon checklist. The explanatory variables were eight items for the built environment at the individual and community levels. To consider each level of built environment simultaneously, multilevel Poisson regression analysis was used to calculate risk ratios and 95% confidence intervals.

Results After 3 years of follow-up, the onset of frailty was 2,740 (7.1%) in 2016. At the individual level, there was an increased risk of developing frailty in negative built environments, such as locations with graffiti or garbage (incidence rate ratio (IRR), 1.15; confidence interval (CI), 1.05–1.25). Positive built environments, such as areas with access to parks and sidewalks (IRR, 0.78; CI, 0.70–0.88), lowered the risk of developing frailty. At the community level, the risk of developing frailty was lower only in areas with locations difficult for walking (hills or steps) (IRR, 0.97; CI, 0.94–0.99).

Conclusions At the individual level, frailty onset was associated with all built environments. However, irrespective of their answers, there was a lower risk of developing frailty among older adults living in areas where walking was difficult. It would be desirable to verify whether the risk of developing frailty can be reduced by changing the built environment.

Introduction

In recent years, there has been growing interest in preventing frailty, an age-related physiological syndrome in which older adults are at an increased risk for health deterioration, including falls, institutionalization, hospitalization, and death [1]. Researchers have, however, found that preventive interventions can prevent or reduce frailty [2]. Most researchers on frailty prevention have focused on individual lifestyle patterns and habits such as exercise and physical activity [3], nutrition [4], and social participation [5]. However, the WHO reports on healthy aging [6], and age friendly cities [7] recommend improving the social environments and community supports around older adults to maintain and improve their health and help them fulfill their potential.

Built environments, that is, areas that were constructed or developed by humans rather than occurring naturally, such as neighborhoods, parks, and streets, have been attracting attention as having associations with health [7]. In a longitudinal study, older adults living in neighborhoods with more green spaces had fewer cases of frailty after 2 years

[8], and the risk of developing frailty was higher in individuals who felt that their housing, residence, neighborhood environment, and noise levels were often poor [9]. In addition, in multilevel (individual and community) cross-sectional analyses, older adults living in areas that were aesthetically pleasing and walkable and that had high land use composition had less frailty [10,11], and there was more frailty in areas with high road connectivity [11].

However, most of the previous studies were conducted at the individual or community level alone, and a multilevel analysis is necessary to clarify the relationships between built environments and the onset of frailty, taking into account the hierarchical structure of the individual and community levels. Moreover, researchers who have examined the relationships between built environments and frailty onset using multilevel analysis have performed only cross-sectional studies, with no longitudinal studies to be found. The purpose of this study is to clarify the relationship between built environments and the onset of frailty after 3 years to better understand how older adults show less frailty simply by living in communities from the perspective of the built environment.

Methods

Study Design

The present study was a three-year longitudinal study using data from the Japan Gerontological Evaluation Study (JAGES) [12]. In 2013 (baseline), we conducted a self-administered mail survey of 138,143 older adults aged 65 years or older living in 22 municipalities in 9 prefectures who were not certified as requiring support or care, and we received responses from 98,243 people (71.1% response rate) (Figure 1). The 22 municipalities include diverse urban and rural areas of Japan. Of these, 93,395 responses were complete after we excluded the 4,848 who had missing personal identification codes, sex, and age. To create the community-level built environment variables, we excluded 38 comunnities and 1,715 people living in comunnities where the area of residence was unknown and the number of respondents per comunnity was less than 30; excluding these individuals left 91,680 respondents living in 562 areas defined primarily by school districts [13]. We also followed 93,395 valid respondents at the individual level for 3 years, and the combined sample totaled 70,603. The final sample for analysis was 38,829 older adults, excluding the 4,742 who had died or required long-term care or support, in addition to those who were frail at baseline. Of the 22 cities and towns, 13 that were relatively small were surveyed at both time points, and the 9 larger ones were surveyed by random sampling. The average follow-up period was 3 years.

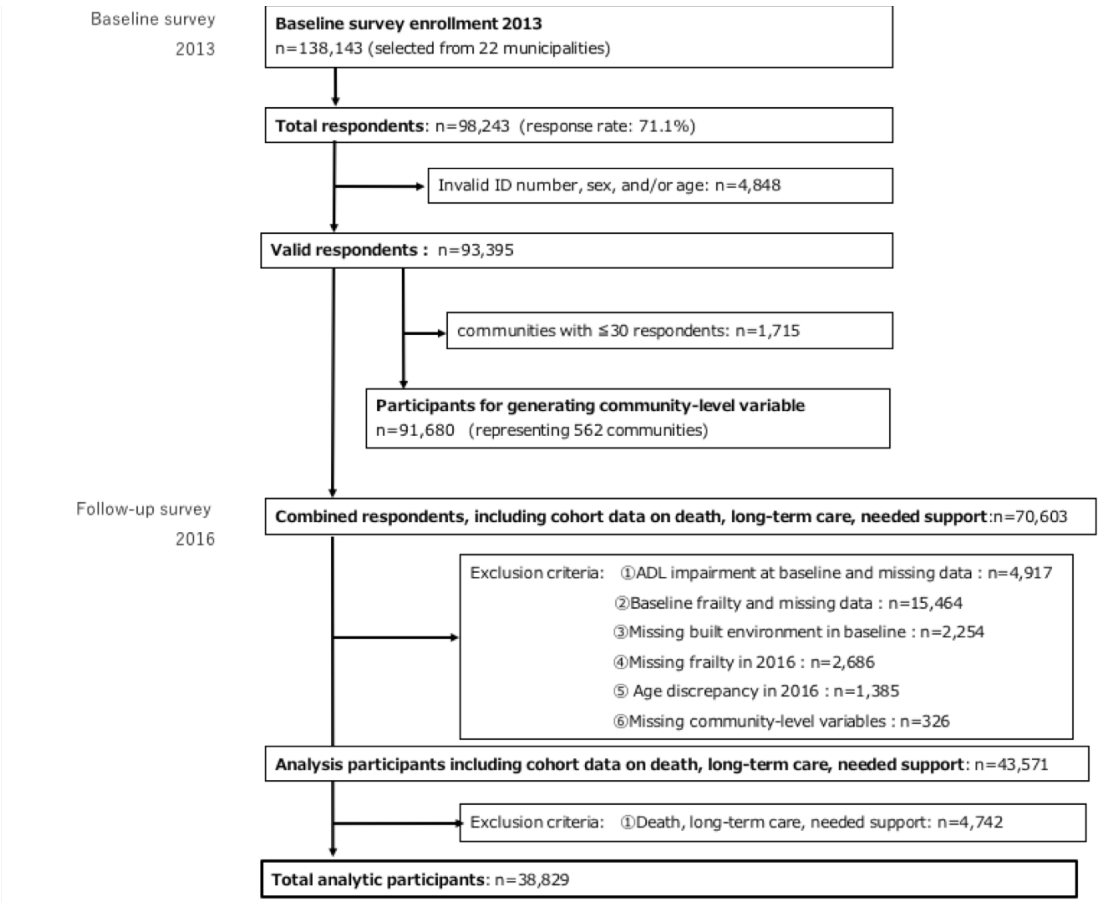

Figure 1. Flow of participants in the longitudinal study.

Measurements

Dependent Variable

The dependent variable was the onset of frailty, and respondents who were frail at follow-up from baseline prefrailty or robust were defined as frailty onset. We used the Kihon checklist (KCL) to determine frailty [14]. It is a self-administered questionnaire with 25 yes-or-no questions worth 1 point for each yes, for a total possible score of 25 points. KCL has seven components (five items for activities related to daily living, five items for locomotion, two items for low nutritional status, three items for oral function, two items for confinement, three items for cognitive function, and five items for depressive mood). 0–3 points for robust, 4–7 points for prefrail, and 8 points or more for frail. In addition, we tested the relationship between the Cardiovascular Health Study criteria based on Fried et al.'s phenotype model [1], which is frequently used as diagnostic criteria for frailty, and the KCL score and found a strong association, with sensitivity and specificity of 89.5% and 80.7%, respectively [15]. The KCL frailty classification has been validated as a predictor of dependency and death in older adults [16]. The contents of the KCL were partially modified by the Japanese Ministry of Health, Labor and Welfare in this study [17,18].

Community- and Individual-Level Independent Variables

The independent variables were eight types of built environments [13]. From the responses to the question, "How many of the following places are there within walking distance (roughly within 1 km) of your house?," which gave respondents a list of response options, we selected four positive and four negative aspects of built environments: negative: "locations with graffiti or garbage," "roads/crossroads with risk of traffic accidents," "dangerous places for walking alone at night," and "locations difficult for walking (hills or steps)"; positive: "access to parks and sidewalks," "fascinating views or buildings," "access to fresh food stores," and "houses or facilities where you feel free to drop in." The potential responses were many, some, few, none, and "I don't know." We dichotomized these five responses into yes (many and some) or no (few, none, and I do not know) and used the eight environment types as individual-level independent variables [13]. We created the community-level variable by dividing the total number of valid responses in each community by the total number of respondents who reported yes for each of the eight built environment types.

Covariates

We created the covariates with reference to previous studies related to social and built environments. The individual-level confounders were sex, age, education, annual equivalent income, disease status in treatment, presence of family members living with the patient, instrumental activities of daily living (IADL), living situation, and job.

Age was categorized by group as 65–69, 70–74, 75–79, 80–84, and ≥85 years [19]. For disease status in treatment, the options were stroke, osteoporosis, hypertension, diabetes, trauma and fracture, joint disease and neuralgia, respiratory disease, and heart disease [20]. We used the the Tokyo Metropolitan Institute of Gerontology Index of Competence (TMIG-IC) as the measure of IADL used in Japan [21]. The TMIG-IC included IADL as a subitem. A score of 3 or more indicates independence in higher life functions and a score of less than 13 indicates nonindependence [18, 22]. For confounders at the community level, population density, annual total daylight, annual rainfall, and deepest annual snowfall amount [23] were calculated by dividing the data into quartile categories. The population density was calculated by equally distributing the population in the 500 m mesh data from the census of the building site using GIS and by equally distributing the population by the neighborhood district polygon [24]. For the amount of annual total daylight, annual rainfall, and deepest annual snowfall, the abovementioned covariates were surveyed in 2010 by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) in Japan, and they used 1 km of mesh data issued in 2012. We conducted a pre-stratification analysis that considered the population density of the residential areas [25]. Education was calculated by aggregating the relevant percentages of respondents who answered "9 years or less" [26] at the individual level by community.

Physical and lifestyle factors [27], social factors [28], and psychological factors [29] have been reported as intermediaries between built environments and health outcomes at the individual level.

We set frequency of going out as less than once/week or more than twice/week [30] and daily walking time as less than 30, 30–59, 60–89, or more than 90 min [31]. We assessed depression using the 15-item Geriatric Depression Scale, with scores above 5 indicating depression, and categorized BMI as <18.5, 18.5–25, or >25 [30]. The frequency of meeting with friends was less than once/month or more than once/month [32], and the frequencies of meat/fish and vegetable/fruit intake were at least once a day, four to six times a week, and less than three times a week [33]. Those who did not respond to any of the variables were considered the nonresponse group.

Statistical Analyses

First, we checked frailty onset at the individual level by each variable and by the presence or absence of each built environment type. Then, we calculated descriptive statistics for each community-level variable and the percentage of each built environment type at the community level. We conducted multilevel Poisson regression analysis at 5% significance to estimate the variations in outcomes across comunnities (random effects) and the impacts of comunnity -level variables while adjusting for individual (level 1) and comunnity (level 2) characteristics (fixed effects). We calculated incidence rate ratios (IRRs) and 95% CIs for frailty onset for individuals and the community-level built environment types. The IRR of the percentage of built environment types at the community level was estimated in units of 10 percentage points of the aggregated percentage of built environment. We used four multivariate models for our analysis. In the crude model, individual- and community-level built environment variables were entered separately, and their cross-level interaction terms were entered. In Model 1, we added both individual-level and community-level confounders. In Model 2, we added individual-level intermediate factors (physical, lifestyle, and social factors). In Model 3, we added depression as the last individual-level intermediate factor.

We also conducted two sensitivity analyses to check the robustness of the results. For the first, we analyzed only the 25,181 subjects who were robust, and we excluded the 13,648 who were prefrail at baseline. For the second, we analyzed the outcome in 43,571 subjects, including not only the frail but also 4,742 subjects who died or who required long-term care or some type of support during the follow-up period. We performed all statistical analyses using STATA 16/PM (Stata Corp LLC, College Station, TX, USA). This study was reviewed and approved by the ethics committees at the University of Tokyo (No. 10555), Nihon Fukushi University (No. 13-14), National Centre for Geriatrics and Gerontology (No. 992), and Chiba University (No. 1777 and 2493). All our procedures conformed to the Declaration of Helsinki.

Results

Of the 38,829 subjects analyzed at baseline (mean age: 72.2 years, 18,590 men and 20,239 women), 2,740 (7.1%) developed frailty after 3 years. Table 1 shows the percentages of frailty onset with each built environment at the individual level. The built environment types associated with the lowest percentages of frailty onset were houses or facilities where you could feel free to drop at 5.9% and fascinating views or buildings at 6.4%.

Table 1. Individual-level built environment types and onset of frailty

Individual-level variables	Total, N	Onset of frailty	
		n	%
Total	38,829	2,740	7.1
Individual-level Built environment			
Locations with graffiti or garbage			
Present	9,283	706	7.6
Absent	29,546	2,031	6.9
Roads/crossroads with risk of traffic accidents			
Present	24,167	1,741	7.2
Absent	14,662	999	6.8
Dangerous places for walking alone at night			
Present	22,500	1,617	7.2
Absent	16,329	1,123	6.9
Locations difficult for walking (hills or steps)			
Present	13,862	1,108	8.0
Absent	24,967	1,632	6.5
Access to parks and sidewalks			
Present	29,501	1,943	6.6
Absent	9,328	797	8.5
Fascinating views or buildings			
Present	16,004	1,017	6.4
Absent	22,825	1,723	7.5
Access to fresh food stores			
Present	30,211	2,028	6.7
Absent	8,618	712	8.3

Houses or facilities where you feel free to drop in			
Present	15,185	897	5.9
Absent	23,644	1,843	7.8

Table 2 shows the percentages of individual-level frailty onset by community-level built environment type. When we calculated the percentage of each built environment type in each area, the means (SD) of the built environments with the highest percentages were 78.6% (16.3%) for access to fresh food stores, 77.7% (14.3%) for access to parks and sidewalks. Supplemental Table 1 presents the descriptive statistics for the explanatory variables at the individual and community levels, and Table 3 shows the results of the multilevel Poisson regression analysis.

Table 2. Percentages of individual-level onset of frailty by community-level built environment type

Community-level built environment type (n = 562 community areas)		
Total	Mean (SD)	(Min–Max)
Locations with graffiti or garbage	23.8% (8.1%)	(2.8%–61.5%)
Roads/crossroads with risk of traffic accidents	61.3% (9.2%)	(13.9%–85.4%)
Dangerous places for walking alone at night	56.7% (9.3%)	(25.5%–83.9%)
Locations difficult for walking (hills or steps)	43.1% (22.8%)	(4.8%–95.3%)
Access to parks and sidewalks	77.7% (14.3%)	(22.9%–100.0%)
Fascinating views or buildings	41.5% (17.3%)	(8.1%–97.8%)
Access to fresh food stores	78.6% (16.3%)	(19.7%–100.0%)
Houses or facilities where you feel free to drop in	33.9% (8.6%)	(10.6%–70.1%)

Supplementary Table 1. Descriptive statistics of individual-level and community-level variables and cumulative onset of frailty

Individual-level variables	Total, N	Onset of frailty	
		N	%
Sex			
Male	18,590	1,259	6.8
Female	20,239	1,481	7.3
Age (yr)			
65–69	13,539	59	4.2
70–74	13,683	766	5.6
75–79	7,716	753	9.8
80–84	3,042	460	15.1
≥85	849	192	22.6
Education (yr)			
<10	13,209	1,279	9.7
10—12	15,865	965	6.1
≥13	9,376	465	5.0
Missing	379	31	8.2
Annual equivalent income (Yen)			
<2,000,000	6,698	718	10.7
2,000,000–3,999,999	14,395	986	6.6
≥4,000,000	12,995	644	5.0
Missing	4,201	393	9.3
Disease status in treatment			
No	7,004	292	4.2
Yes	29,755	2,347	7.9
Missing	2,070	101	4.9
Instrumental activities of daily living			
Non-independent	4,429	662	14.9
Independent	33,519	1,955	5.8
Missing	881	123	14.0
Living situation			

Lives alone	4,249	372	8.8
Lives with others	32,866	2,190	6.7
Missing	1,714	178	10.4
Job			
No	26,603	2,014	7.6
Having	10,133	507	5.0
Missing	2,093	219	10.5
Frequency of going out			
≥1 time/day	1,114	162	14.5
<1 time/day	37,636	2,569	6.8
Missing	79	9	11.4
Daily walking time (min)			
<30	6,960	751	10.8
30–59	14,535	1,033	7.1
60–89	8,175	475	7.1
≥90	8,967	460	5.1
Missing	192	21	10.9
Depression			
No (GDS <5)	29,593	1,528	5.2
Yes (GDS ≥5)	5,372	882	16.4
Missing	3,864	330	8.0
Body mass index (kg/m2)			
<18.5	2,110	229	10.9
18.5~24	27,336	1,763	6.4
≥25	8,169	646	7.9
Missing	1,214	102	8.4
Driving status			
No	19,286	1,479	7.2
Yes	19,537	1,360	7.0
Missing	6	1	16.7
Social participation			
<1time/month	13,567	1,250	9.2

≥1time/month	22,645	1,258	5.6
Missing	2,617	232	8.9
Frequency of meeting with friends			
<1time/month	8,330	804	9.7
≥1time/month	29,519	1,841	6.2
Missing	980	95	9.7
Frequency of meat/fish intake			
≤3times/week	9,512	811	8.5
4times/week-6time/week	9,670	736	7.6
≥1 time/day	19,313	1,176	6.1
Missing	334	17	5.1
Frequency of vegetable/fruit intake			
≤3times/week	2,291	215	9.4
4times/week-6time/week	4,275	393	9.2
≥1 time/day	32,106	2,114	6.6
Missing	157	18	11.5
Social support			
No	14,458	1,265	9.7
Yes	22,704	1,321	5.8
Missing	1,667	154	9.2
Community-level variables	n	Onset of frailty (%)	
Total	562	6.9	
Population density (persons per square km of inhabitable area)			
Highest quartile(≥11,438)	140	6.8	
Second quartile(9,066–11,437)	141	6.3	
Third quartile(5,711–9,065)	141	7.2	
Lowest quartile(<5,711)	140	7.2	
Annual total daylight (hours)			
Highest quartile(≥2,077)	140	6.6	
Second quartile(2,048–2,076)	141	6.8	
Third quartile(1,918–2,047)	141	6.4	

Lowest quartile(<1,918)	140		7.6
Annual rainfall (mm)			
Highest quartile(≥1616)	140		7.0
Second quartile(1,522–1,615)	141		6.9
Third quartile(1,490–1,521)	141		6.8
Lowest quartile(<1,490)	140		6.8
Deepest annual snowfall amount (cm)			
Highest quartile(≥4)	140		7.4
Second quartile(2–3)	96		6.7
Third quartile(1.8–2)	118		6.2
Lowest quartile(<1.8)	208		6.9
Education			
Mean (SD)		35.1%	(15.5%)
(Min–Max)		(0.0%–86.4%)	

At the individual level, we found significant associations for all built environment variables in Model 1, which adjusted for confounders, and in Model 2, which adjusted for intermediate factors other than depression. In Model 3, which adjusted for intermediate factors, including depression, the association disappeared only for fascinating views or buildings. At the community level, the crude model showed that the risk of developing frailty was lower in areas with high percentages of roads/crossroads with risk of traffic accidents (IRR, 0.93; 95% CI, 0.88–0.98), those with dangerous places for walking alone at night (0.94; 0.90–0.99), and those with locations that are difficult for walking (hills or steps) (0.96; 0.94–0.98). In Models 1 and 2, the risk of frailty onset was reduced only where there were high percentages of areas with locations difficult for walking (hills or steps) (Model 1: 0.97; 0.94–0.99, Model 2: 0.97; 0.94–0.99). The results of the sensitivity analysis limited to robust respondents and excluding baseline prefrailty showed that 602 (2.4%) people developed frailty, and the results of the multilevel Poisson regression analysis were generally similar to those from the main analysis at the individual level.

At the community level, Models 1 and 2 showed a lower risk of developing frailty in locations with high percentages of areas that were difficult for walking (Supplemental Table 2). In a sensitivity analysis in which the outcome included not only frailty but also death, long-term care, and needed support during the follow-up period, the number of patients who became frail, died, needed long-term care, or needed support was 6,482 (17.2%). The multilevel

Poisson regression analysis showed that at the individual level, in Model 1, the presence of locations difficult for walking (hills or steps) (1.09; 1.03–1.14) increased the risk of developing frailty. Access to parks and sidewalks (0.86; 0.80–0.92) decreased frailty risk (Supplemental Table 3).

Table 3. Multilevel Poisson regression analysis of frailty onset and individual-level and community-level built environment type (participants nested in 562 community areas).

n=38,829	Crude			Model 1			Model 2			Model 3		
	IRR	95% CI	P	IRR	95% CI	P	IRR	95% CI	P	IRR	95% CI	P
Locations with graffiti or garbage												
Individual-level	1.10	1.01 – 1.20	0.028	1.15	1.05 – 1.25	0.002	1.18	1.08 – 1.29	<0.001	1.15	1.05 – 1.25	0.002
Community-level *	1.03	0.97 – 1.10	0.273	1.01	0.95 – 1.07	0.749	0.99	0.93 – 1.06	0.850	0.98	0.92 – 1.04	0.537
Cross-level interaction	0.96	0.84 – 1.09	0.500	0.99	0.87 – 1.13	0.861	1.00	0.87 – 1.13	0.945	1.00	0.88 – 1.14	0.971
Roads/crossroads with risk of traffic accidents												
Individual-level	1.05	0.97 – 1.14	0.199	1.13	1.04 – 1.22	0.004	1.15	1.06 – 1.26	<0.001	1.13	1.04 – 1.22	0.004
Community-level *	0.93	0.88 – 0.98	0.010	1.00	0.95 – 1.06	0.899	0.99	0.94 – 1.05	0.849	0.99	0.93 – 1.05	0.784
Cross-level interaction	0.89	0.80 – 0.99	0.027	0.92	0.83 – 1.02	0.099	0.92	0.83 – 1.02	0.119	0.93	0.84 – 1.03	0.192
Dangerous places for walking alone at night												
Individual-level	1.05	0.97 – 1.14	0.220	1.15	1.06 – 1.25	0.004	1.17	1.08 – 1.27	<0.001	1.12	1.04 – 1.22	0.004
Community-level *	0.94	0.90 – 0.99	0.030	1.00	0.95 – 1.05	0.899	1.00	0.95 – 1.05	0.891	1.00	0.95 – 1.05	0.901
Cross-level interaction	0.94	0.85 – 1.03	0.172	0.95	0.87 – 1.04	0.099	0.95	0.86 – 1.04	0.265	0.94	0.86 – 1.04	0.218
Locations difficult for walking (hills or steps)												
Individual-level	1.30	1.19 – 1.42	<0.001	1.23	1.12 – 1.34	<0.001	1.24	1.13 – 1.35	<0.001	1.19	1.09 – 1.30	<0.001
Community-level *	0.96	0.94 – 0.98	0.001	0.97	0.94 – 0.99	0.030	0.97	0.94 – 0.99	0.044	0.98	0.95 – 1.01	0.101
Cross-level interaction	0.98	0.94 – 1.03	0.510	0.98	0.94 – 1.03	0.489	0.98	0.93 – 1.03	0.394	0.99	0.94 – 1.04	0.613

Access to parks and sidewalks															
Individual-level	0.73	0.65	–	0.82	<0.001	0.78	0.70	–	0.88	<0.001	0.82	0.73	–	0.92	0.001	0.86	0.76	–	0.96	0.011
Community-level *	1.00	0.97	–	1.03	0.853	1.03	0.99	–	1.07	0.160	1.03	0.99	–	1.07	0.167	1.03	0.99	–	1.07	0.166
Cross-level interaction	0.95	0.88	–	1.01	0.122	0.96	0.89	–	1.03	0.209	0.96	0.90	–	1.03	0.272	0.97	0.90	–	1.04	0.346
Fascinating views or buildings															
Individual-level	0.81	0.75	–	0.88	<0.001	0.88	0.81	–	0.96	0.003	0.92	0.85	–	0.99	0.049	0.97	0.90	–	1.06	0.521
Community-level *	1.03	1.00	–	1.06	0.058	1.02	0.99	–	1.05	0.266	1.02	0.99	–	1.05	0.269	1.02	0.99	–	1.05	0.310
Cross-level interaction	0.95	0.90	–	1.01	0.086	0.96	0.91	–	1.02	0.228	0.97	0.91	–	1.03	0.294	0.97	0.91	–	1.03	0.275
Access to fresh food stores															
Individual-level	0.76	0.68	–	0.85	<0.001	0.82	0.73	–	0.91	<0.001	0.83	0.74	–	0.93	0.001	0.87	0.78	–	0.97	0.013
Community-level *	1.01	0.99	–	1.04	0.367	1.03	1.00	–	1.06	0.073	1.02	0.99	–	1.05	0.157	1.02	0.99	–	1.05	0.257
Cross-level interaction	0.95	0.90	–	1.01	0.093	0.98	0.93	–	1.04	0.502	0.98	0.93	–	1.04	0.553	0.98	0.93	–	1.04	0.531
Houses or facilities where you feel free to drop in															
Individual-level	0.74	0.68	–	0.81	<0.001	0.79	0.72	–	0.86	<0.001	0.85	0.78	–	0.93	<0.001	0.92	0.84	–	0.99	0.050
Community-level *	1.09	1.03	–	1.15	0.001	1.04	0.98	–	1.10	0.182	1.04	0.98	–	1.10	0.179	1.05	0.99	–	1.10	0.114
Cross-level interaction	0.99	0.89	–	1.10	0.841	0.97	0.87	–	1.08	0.596	0.96	0.86	–	1.08	0.518	0.97	0.87	–	1.08	0.562

IRR: Incidence rate ratio; CI: Confidence interval

*IRR for 10 percentage point increase in the percentage of the school district with a built environment.

Model 1：crude model ＋【Community-level】 population density, annual total daylight, annual rainfall, deepest annual snowfall amount, education

【Individual-Level】 sex, age, education, annual equivalent income, disease status in treatment, instrumental activities of daily living, living situation, job

Model 2：model1 ＋daily walking time, driving status, frequency of meeting with friends, frequency of meat/fish intake, body mass index,

frequency of Social participation, social support, frequency of meeting with friends, frequency of going out

Model 3：model2 ＋depression

Individual-level and community-level built environment variables were entered separately, and their cross-level interaction terms were entered.

Supplementary Table 2. Results of multilevel poisson regression analysis of frailty onset and Individual-level and community-level built environment with robust older as the baseline

n=25,181	Crude			Model 1			Model 2			Model 3		
	IRR	95% CI	P	IRR	95% CI	P	IRR	95% CI	P	IRR	95% CI	P
Locations with graffiti or garbage												
Individual-level	1.10	1.01 – 1.20	0.028	1.15	1.05 – 1.25	0.002	1.19	1.09 – 1.30	<0.001	1.15	1.05 – 1.25	0.002
Community-level *	1.03	0.97 – 1.10	0.273	1.01	0.95 – 1.08	0.695	1.00	0.94 – 1.06	0.918	0.98	0.92 – 1.05	0.600
Cross-level interaction	0.96	0.84 – 1.09	0.500	0.99	0.87 – 1.13	0.901	1.00	0.88 – 1.14	0.977	1.01	0.88 – 1.15	0.938
Roads/crossroads with risk of traffic accidents												
Individual-level	1.05	0.97 – 1.14	0.199	1.13	1.04 – 1.22	0.004	1.16	1.07 – 1.26	<0.001	1.13	1.04 – 1.22	0.004
Community-level *	0.93	0.89 – 0.98	0.010	1.01	0.95 – 1.07	0.849	1.00	0.94 – 1.06	0.908	0.99	0.94 – 1.05	0.844
Cross-level interaction	0.89	0.80 – 0.99	0.027	0.92	0.83 – 1.02	0.103	0.92	0.83 – 1.02	0.120	0.93	0.84 – 1.03	0.193
Dangerous places for walking alone at night												
Individual-level	1.05	0.97 – 1.14	0.220	1.15	1.06 – 1.25	0.001	1.17	1.08 – 1.27	<0.001	1.12	1.04 – 1.22	0.005
Community-level *	0.95	0.90 – 0.99	0.030	1.00	0.95 – 1.05	0.862	1.00	0.95 – 1.05	0.917	1.00	0.95 – 1.05	0.927
Cross-level interaction	0.94	0.85 – 1.03	0.172	0.95	0.87 – 1.04	0.293	0.95	0.86 – 1.04	0.267	0.94	0.86 – 1.04	0.219
Locations diffcult for walking (hills or steps)												
Individual-level	1.30	1.19 – 1.42	<0.001	1.23	1.12 – 1.34	<0.001	1.24	1.14 – 1.35	<0.001	1.19	1.09 – 1.30	<0.001
Community-level *	0.96	0.94 – 0.99	0.001	0.97	0.95 – 1.00	0.030	0.97	0.95 – 1.00	0.047	0.98	0.95 – 1.00	0.109
Cross-level interaction	0.98	0.94 – 1.03	0.510	0.98	0.94 – 1.03	0.525	0.98	0.93 – 1.03	0.433	0.99	0.94 – 1.04	0.653

Access to parks and sidewalks															
Individual-level	0.73	0.65	– 0.82	<0.001	0.78	0.70	– 0.88	<0.001	0.82	0.73	– 0.92	0.001	0.86	0.76	– 0.96	0.010
Community-level *	1.00	0.97	– 1.03	0.853	1.03	0.99	– 1.07	0.153	1.03	0.99	– 1.07	0.147	1.03	0.99	– 1.07	0.143
Cross-level interaction	0.95	0.88	– 1.01	0.122	0.96	0.89	– 1.02	0.196	0.96	0.90	– 1.03	0.247	0.96	0.90	– 1.03	0.312
Fascinating views or buildings															
Individual-level	0.81	0.75	– 0.88	<0.001	0.88	0.81	– 0.96	0.003	0.92	0.85	– 1.00	0.050	0.97	0.89	– 1.06	0.514
Community-level *	1.03	1.00	– 1.06	0.058	1.02	0.99	– 1.05	0.284	1.02	0.99	– 1.05	0.275	1.02	0.99	– 1.05	0.304
Cross-level interaction	0.95	0.90	– 1.01	0.086	0.96	0.91	– 1.02	0.232	0.97	0.91	– 1.03	0.290	0.97	0.91	– 1.03	0.265
Access to fresh food stores															
Individual-level	0.76	0.68	– 0.85	<0.001	0.82	0.73	– 0.91	<0.001	0.83	0.74	– 0.92	0.001	0.87	0.78	– 0.97	0.011
Community-level *	1.01	0.99	– 1.04	0.367	1.03	1.00	– 1.06	0.068	1.02	0.99	– 1.05	0.144	1.02	0.99	– 1.05	0.235
Cross-level interaction	0.95	0.90	– 1.01	0.093	0.98	0.93	– 1.04	0.505	0.98	0.93	– 1.04	0.557	0.98	0.93	– 1.04	0.540
Houses or facilities where you feel free to drop in															
Individual-level	0.74	0.68	– 0.81	<0.001	0.79	0.73	– 0.86	<0.001	0.85	0.78	– 0.93	<0.001	0.92	0.84	– 1.00	0.058
Community-level *	1.09	1.04	– 1.15	0.001	1.04	0.98	– 1.10	0.194	1.04	0.98	– 1.10	0.197	1.04	0.99	– 1.10	0.126
Cross-level interaction	0.99	0.89	– 1.10	0.841	0.97	0.87	– 1.08	0.538	0.96	0.86	– 1.07	0.460	0.96	0.86	– 1.07	0.499

IRR: Incidence rate ratio; CI: Confidence interval

*IRR for 10 percentage point increase in the percentage of the school district with a built environment.

Model 1：crude model ＋【Community-level】 population density, annual total daylight, annual rainfall, deepest annual snowfall amount, education

【Individual-Level】 sex, age, education, annual equivalent income, disease status in treatment, instrumental activities of daily living, living situation, job

Model 2：model1 ＋daily walking time, driving status, frequency of meeting with friends, frequency of meat/fish intake, body mass index, frequency of Social participation, social support, frequency of meeting with friends, frequency of going out

Model 3：model2 ＋depression

Individual-level and community-level built environment variables were entered separately, and their cross-level interaction terms were entered.

Supplementary Table 3. Multilevel poisson regression analysis of death, long-term care, needed support, and onset of frailty and individual-level and community-level built environment types

n=43,571	Crude			Model 1			Model 2			Model 3		
	IRR	95% CI	P	IRR	95% CI	P	IRR	95% CI	P	IRR	95% CI	P
Locations with graffiti or garbage												
Individual-level	0.94	0.89 – 0.99	0.025	1.00	0.95 – 1.06	0.961	1.02	0.97 – 1.08	0.387	1.01	0.95 – 1.07	0.760
Community-level *	1.04	0.99 – 1.08	0.104	1.05	1.00 – 1.10	0.038	1.04	1.00 – 1.09	0.069	1.04	0.99 – 1.09	0.086
Cross-level interaction	0.97	0.89 – 1.05	0.410	1.00	0.92 – 1.08	0.984	1.01	0.93 – 1.09	0.865	1.01	0.93 – 1.10	0.800
Roads/crossroads with risk of traffic accidents												
Individual-level	0.97	0.92 – 1.02	0.196	1.02	0.97 – 1.07	0.407	1.05	1.00 – 1.10	0.058	1.03	0.98 – 1.08	0.202
Community-level *	1.00	0.96 – 1.04	0.878	1.03	0.99 – 1.08	0.164	1.03	0.98 – 1.07	0.213	1.03	0.98 – 1.07	0.229
Cross-level interaction	0.96	0.90 – 1.03	0.263	0.98	0.92 – 1.04	0.509	0.99	0.93 – 1.05	0.747	0.99	0.93 – 1.06	0.856
Dangerous places for walking alone at night												
Individual-level	0.91	0.87 – 0.96	<0.001	1.01	0.97 – 1.06	0.561	1.03	0.99 – 1.08	0.174	1.01	0.97 – 1.06	0.595
Community-level *	0.99	0.95 – 1.03	0.585	1.01	0.97 – 1.05	0.645	1.01	0.97 – 1.05	0.681	1.01	0.97 – 1.05	0.694
Cross-level interaction	1.01	0.95 – 1.07	0.842	1.01	0.95 – 1.07	0.832	1.01	0.95 – 1.07	0.845	1.00	0.94 – 1.06	0.959
Locations diffcult for walking (hills or steps)												
Individual-level	1.17	1.11 – 1.23	<0.0010	1.09	1.03 – 1.14	0.001	1.10	1.05 – 1.16	<0.001	1.08	1.03 – 1.14	0.003
Community-level *	0.98	0.96 – 1.00	0.013	0.99	0.97 – 1.01	0.762	1.00	0.98 – 1.01	0.609	1.00	0.98 – 1.02	0.796
Cross-level interaction	0.99	0.96 – 1.02	0.399	0.98	0.95 – 1.01	0.421	0.99	0.96 – 1.02	0.335	0.99	0.96 – 1.02	0.415

Access to parks and sidewalks														
Individual-level	0.80	0.74	– 0.86	<0.001	0.86	0.80	– 0.92	<0.001	0.89	0.83	– 0.96	0.002	0.91	0.84	– 0.97	0.007
Community-level *	1.00	0.98	– 1.03	0.744	1.03	0.95	– 1.05	0.062	1.02	0.93	– 1.06	0.087	1.02	0.93	– 1.02	0.012
Cross-level interaction	0.94	0.90	– 0.99	0.008	0.97	0.93	– 1.01	0.172	0.97	0.93	– 1.02	0.218	0.97	0.93	– 1.02	0.234
Fascinating views or buildings														
Individual-level	0.90	0.85	– 0.94	<0.001	0.95	0.91	– 1.00	0.052	0.99	0.94	– 1.04	0.563	1.01	0.96	– 1.06	0.745
Community-level *	1.01	0.99	– 1.03	0.488	1.00	0.98	– 1.03	0.745	1.00	0.98	– 1.03	0.851	1.00	0.98	– 1.02	0.890
Cross-level interaction	0.96	0.92	– 0.99	0.011	0.97	0.93	– 1.00	0.068	0.97	0.93	– 1.00	0.064	0.96	0.93	– 1.00	0.048
Access to fresh food stores														
Individual-level	0.85	0.79	– 0.91	<0.001	0.91	0.85	– 0.97	0.007	0.93	0.87	– 0.99	0.031	0.95	0.89	– 1.02	0.133
Community-level *	1.01	0.99	– 1.03	0.515	1.01	0.99	– 1.04	0.228	1.01	0.99	– 1.03	0.350	1.01	0.99	– 1.03	0.424
Cross-level interaction	0.95	0.92	– 0.98	0.003	0.98	0.95	– 1.01	0.237	0.98	0.95	– 1.01	0.274	0.98	0.95	– 1.01	0.273
Houses or facilities where you feel free to drop in														
Individual-level	0.89	0.85	– 0.93	<0.001	0.92	0.87	– 0.97	0.001	0.97	0.92	– 1.02	0.269	1.00	0.96	– 1.06	0.848
Community-level *	1.00	0.96	– 1.04	0.839	0.99	0.95	– 1.03	0.646	0.99	0.95	– 1.03	0.657	0.99	0.95	– 1.03	0.761
Cross-level interaction	0.95	0.89	– 1.01	0.124	0.95	0.89	– 1.01	0.089	0.94	0.88	– 1.00	0.053	0.94	0.88	– 1.00	0.053

IRR: Incidence rate ratio; CI: Confidence interval

*IRR for 10 percentage point increase in the percentage of the school district with a built environment.

Model 1：crude model ＋【Community-level】 population density, annual total daylight, annual rainfall, deepest annual snowfall amount, education

【Individual-Level】 sex, age, education, annual equivalent income, disease status in treatment, instrumental activities of daily living, living situation, job

Model 2：model1 ＋daily walking time, driving status, frequency of meeting with friends, frequency of meat/fish intake, body mass index, frequency of Social participation, social support, frequency of meeting with friends, frequency of going out

Model 3：model2 ＋depression

Individual-level and community-level built environment variables were entered separately, and their cross-level interaction terms were entered.

Discussion

In this study, we examined relationships between built environments and the onset of frailty at the individual and community levels using data from a sample of the respondents to the 2013 wave of the JAGES. When we followed up in 2016, the main result was that the onset of frailty was 7.1% and that individual-level frailty risk was high in the four negative built environment types and lower in the four positive types (Model 1). However, at the community level, older adults living in areas with 10% more locations that were difficult for walking had a 3% lower risk of developing frailty at 3 years, even after we adjusted for individual levels (Model 1).

The individual-level negative built environment variables that increased the risk of developing frailty were locations with graffiti or garbage, roads/crossroads with risk of traffic accidents, dangerous places for walking alone at night, and locations difficult for walking (hills or steps). Previous studies have shown that neighborhood traffic-related safety is highly associated with physical activity, walking, and good mental health [34] and that crime-related safety is associated with less depression [35], consistent with our findings of increased frailty risk associated with these neighborhood factors.

By contrast, the positive individual-level built environment variables that reduced the risk of developing frailty in this study were access to parks and sidewalks, fascinating views or buildings, access to fresh food stores, and houses or facilities where you feel free to drop in were recognized. In previous studies, older adults who lived near parks tended to exercise more frequently [36] . Researchers have also reported that older adults who perceive grocery stores to be nearby are less likely to require long-term care [31] or die [30]. Even if the outcome is frailty, which is a prelude to dementia onset and the need for long-term care, it is clear that these built environments suppress the risk of developing frailty.

Model 3, which included depression as an individual-level intermediate factor, showed weaker IRRs for all built environment variables compared to Model 2. Therefore, it is possible that these intermediate factors explain part of the association between the built environment and frailty.

One notable result from the regression analysis was that individuals who perceive difficulty walking in their neighborhoods are more likely to refrain from going out, which increases the risk of developing frailty, but at the community level, older adults living in areas with 10% more hills and steps showed a lower risk of frailty (Model 1). Previous researchers found in multilevel analyses that more hills and steps in a community are associated with increased weight gain [37] and increased knee pain [19], but others found that steeper slopes in a comunnity were associated with more physical activity such as walking and lower risk of poorly controlled diabetes [32, 38, 39]. The outcome of the present study was frailty, which is related to these health outcomes [40], and researchers have found that resistance exercise with added load is effective in preventing frailty [41]. These findings combined suggest that even though individuals who are aware of hills and steps in their neighborhoods might be avoiding going out, the presence of those hills and steps at the community level unconsciously suppresses frailty onset because of the moderate resistance exercise required to get around on foot. The fact that individuals perceive that there are many hills and steps and that they live in a community with many hills and steps may capture different aspects of the situation. Furthermore, interaction terms with individual and community levels were not significant for all built-environment variables. We consider the combination of the two factors unlikely to be associated with frailty. If a place has a rich built environment at the community level, the risk of developing frailty is lower regardless of the individual's

perception of that environment. In other words, a rich built environment might naturally have a preventive effect on frailty even without the individual's awareness.

The results of the sensitivity analysis, in which the outcome was robust only, excluding baseline prefrailty, showed generally similar results to the main analysis at both the individual and individual levels: Individuals who were prefrail were more likely to become frail than were robust people [42], and the fact that we obtained the same results even after excluding these factors could negate the proposal that older adults who are more likely to become frail are less likely to be aware of their built environments. In a sensitivity analysis—which includes death, long-term care, and required support during the follow-up period as outcomes—in addition to frailty, the characteristics of the population may differ from the results of the main analysis because the population includes people who are more likely to die or need nursing care and support.

Our study has three strengths. First, it is a large-scale survey study covering 9 prefectures and 22 cities and towns in Japan. Second, it uses data at two time points, 3 years after the baseline, thus accounting for time factors. Third, the study employs a multilevel analysis to consider both individual and comunnity factors.

We note three limitations of this study. First, we assessed built environment characteristics based on subjective evaluation. More detailed verification may be possible by considering objective indicators in conjunction with subjective evaluations of the built environment. However, previous research, subjective rather than objective evaluations of built environments were associated with mortality [43]. It is possible that subjective evaluations more closely reflect how cognizant people are of their environments and of the realities of navigating those environments. Second, the KCL that we used to determine frailty in this study differs from the questionnaire used by Satake et al. [15,16], which has been validated in relation to frailty criteria, but the difference is minor. in addition, increasing number of researchers are using frailty as an outcome [17,18]. Third, a selection bias might have affected the results in that the total analytic participants were biased toward the younger, more educated, and higher earning and independent in IADL to the exclusion of the other subjects. The observed results might have been underestimated accordingly, and a stronger association might have been confirmed if participants had not been excluded.

Conclusion

In this study, we investigated the relationships between built environment variables and the onset of frailty at the individual and community levels among older adults living in 22 cities and 562 communities in Japan. At the individual level, the negative aspects of the built environment such as locations with graffiti or garbage and roads/crossroads with risk of traffic accidents increased the onset of frailty, whereas positive aspects such as access to parks and sidewalks, and houses or facilities where you feel free to drop in reduced the onset. At the community level, older adults living in areas with 10% more hills and steps had a 3% lower risk of developing frailty after 3 years, even after we adjusted for individual perceptions of difficulty walking in neighborhoods with hills and steps.

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Author Contribution

Conception and design: YM and TT; data collection: MH and KK; analysis, interpretation of the data, and writing the article: YM; critical revision of the article: YM, TT, RW, MH, TM, and KK. All authors read and approved the final manuscript.

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