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Effects of the leisure-time physical activity environment on odds of glycemic control among a nationwide cohort of United States veterans with a new type-2 diabetes diagnosis

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ABSTRACT

Objective. This study examined associations between access to leisure-time physical activity (LTPA) facilities and parks and repeated measures of glycated hemoglobin (A1C) over time, using follow-up tests among United States Veterans with newly diagnosed type-2 diabetes (T2D). **Methods.** Data were analyzed from 274,463 patients in the Veterans Administration Diabetes Risk cohort who were newly diagnosed with T2D between 2008 and 2018 and followed through 2023. Generalized estimating equations with a logit link function and binomial logistic regression were used to examine associations. **Results.** Patients were on average 60.5 years of age, predominantly male (95.0 %) and white (66.9 %), and had an average of 11.7 A1C tests during the study follow-up period. In high- and low-density urban communities, a one-unit higher LTPA facility density score was associated with 1 % and 3 % greater likelihood of in-range A1C tests during follow-up, respectively, but no association was observed among patients living in suburban/small town and rural communities. Across community types, closer park distance was not associated with subsequent greater odds of in-range A1C tests. Unexpectedly, in low-density urban areas, the likelihood of in-range A1C tests was 1 % lower at farther park distances. **Conclusions.** These results suggest that broader access to LTPA facilities, but not park proximity, may contribute in small ways to maintaining glycemic control after T2D diagnosis in urban communities. Tailored interventions may be needed to promote patients' effective use of LTPA facilities and parks.

1. Introduction

Type 2 diabetes (T2D) is among the top 10 causes of death in the United States where 14.3 % of adults in are diagnosed and another 1–2 % are not yet diagnosed (Wang et al., 2021). The majority of adults with T2D experience comorbidities including hypertension, overweight/obesity, and hyperlipidemia, which further increase mortality risk. Variability in glycated hemoglobin or HbA1c (A1C) over time, a measure of blood glucose stability, contributes to T2D complications and mortality (Prentice et al., 2016; Orsi et al., 2018). Longitudinal cohort studies demonstrate that groups with A1C trajectories with more out-of-range values have worse outcomes, including T2D microvascular and

Abbreviations: T2D, Type 2 diabetes; LTPA, Leisure-time physical activity; A1C, Glycated hemoglobin; VADR, Veteran's administration diabetes risk cohort; GEE, Generalized estimating equations.

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macrovascular events and all-cause mortality (Laiteerapong et al., 2017). In older patients, maintaining A1C levels within a therapeutic range is associated with lower risk of complications and mortality (Prentice et al., 2021; Saboo et al., 2021). From 2017 to 2018, as few as two in three adults with T2D achieved, let alone maintained, individualized A1C targets, with lower prevalence of glycemic control among non-Hispanic blacks and Mexican Americans compared to non-Hispanic whites (Wang et al., 2021).

Healthcare providers encourage patients with T2D to achieve glycemic control through adherence to medication and health behaviors including healthy eating and physical activity (ADAPPC, 2021). Habitual physical activity is an individual-level protective factor against diabetes incidence (Smith et al., 2016) and a contributing mechanism toward diabetes management and control (Pai et al., 2012). The neighborhood built environment (e.g., walkability and access to physical activity resources) is a critical antecedent of physical activity behavior thought to exert potential effects through social cognitions like perceptions of accessibility, self-efficacy, and behavioral intention (Rhodes et al., 2020). Access to recreational facilities is one of the environmental factors most consistently examined and associated with total physical activity and leisure-time physical activity (LTPA) (Orstad et al., 2016). Access to neighborhood facilities and parks may help to ward off age-related declines in physical activity levels (Ranchod et al., 2014; Barnett et al., 2017) and risk of chronic health conditions like T2D (Chandrabose et al., 2019; Moon et al., 2023). Inequitable access may contribute to disparities in physical activity and chronic disease by racial/ethnic group and geographic region in the United States (Jones et al., 2015).

The American Diabetes Association recognizes the role of and need to investigate social and environmental factors in the prevention and management of T2D (Hill-Briggs et al., 2020). Epidemiological evidence of associations between the neighborhood physical activity environment and lower incidence and prevalence of T2D is mixed (Chandrabose et al., 2019; Bilal et al., 2018; den Braver et al., 2018). Evidence seems sufficient to suggest epidemiologic associations between walkability and lower T2D risk (conceptualized via increased physical activity for transportation) (Chandrabose et al., 2019; Horwitz and Retnakaran, 2021; India-Aldana et al., 2022), while data are insufficient to determine the role of the recreational environment and various T2D outcomes (conceptualized via increased LTPA) (Hill-Briggs et al., 2020). More frequent participation in leisure-time activities commonly supported by recreational spaces (walking, yoga, and tai chi) reduces A1C levels in adults with T2D (Pai et al., 2016; Park et al., 2020). Thus, two clear gaps in the evidence to-date are examination of 1) aspects of the recreational physical activity environment on T2D outcomes and 2) the neighborhood physical activity environment as it relates to glycemic control in adults with T2D.

Studies examining the association between recreational facilities and A1C levels are limited. In one study of 15,308 Pennsylvanian primary care patients with T2D, authors found no evidence that higher township density of recreational establishments and parks was associated with reductions in A1C at six or 24 months (Hirsch et al., 2018). In another sample of 615 Veterans with T2D living in Southeastern states, self-reported availability of recreational facilities was not associated with A1C obtained from electronic medical records (Smalls et al., 2015). In these studies, two or fewer A1C time points were examined after T2D diagnosis. Also, examinations of neighborhood social and physical environments and T2D and have been limited to a few data sources, none of which are nationwide cohorts and only two of which utilized geographic information systems-based measures (Christine et al., 2015; Gebreab et al., 2017). Since adjusting for neighborhood socioeconomic status attenuates associations between physical activity facilities and T2D incidence (Christine et al., 2015; Cereijo et al., 2023), there is also a need to examine potential moderating effects of the neighborhood socioeconomic environment. Finally, neighborhood and health associations may differ by urbanicity (Jagai et al., 2020; Kanchi et al., 2021; McAlexander et al., 2022). Therefore, the objective of this study was to examine associations between newly diagnosed T2D patients' access to LTPA facilities and parks and the likelihood that repeated A1C follow-up tests after diagnosis were within a desired range. We examined associations separately across four community types in a nationwide cohort of United States Veterans. We hypothesized that patients with greater access to physical activity facilities and parks vs. those with lesser access would have higher odds of glycemic control after T2D diagnosis.

2. Methods

2.1. Cohort and study sample

This study examines a subsample of patients with T2D from the Veteran's Administration Diabetes Risk (VADR) cohort. VADR is a dynamic retrospective cohort established from the electronic health records of all patients nationally who received primary care services in the Veterans Health Administration from 2008 to 2018 and were diabetes-free upon enrollment (Avramovic et al., 2020). Eligibility criteria included having at least two diabetes-free primary care visits at least 30 days apart in the preceding five years. Patients were excluded if they did not have an address in the contiguous United States on record prior to or within two years after cohort entry, or if during the study period they changed states for clinical care, were deceased, or were lost to follow-up after no healthcare encounters for two years. From VADR, we identified 543,437 patients who received a new T2D diagnosis, defined as: 1) at least two separate healthcare encounters with T2D-specific International Classification of Diseases 9/10 codes, or 2) at least one encounter with T2D-specific codes and at least two elevated Hemoglobin A1C measures (≥6.5 %), or 3) at least one prescription for T2D medication other than Metformin or Acarbose alone (Avramovic et al., 2020). We followed patients from new T2D diagnosis until October 6, 2023 and retained those with at least two A1C tests during follow-up in the analytic sample. (See Fig. 1). All research procedures were approved by the Veterans Administration Institutional Review Board (study number 1667) and the NYU Grossman School of Medicine Institutional Review Board (study number s17–01428).

2.2. Environmental exposures

Patient addresses were geocoded using Esri ArcGIS Application

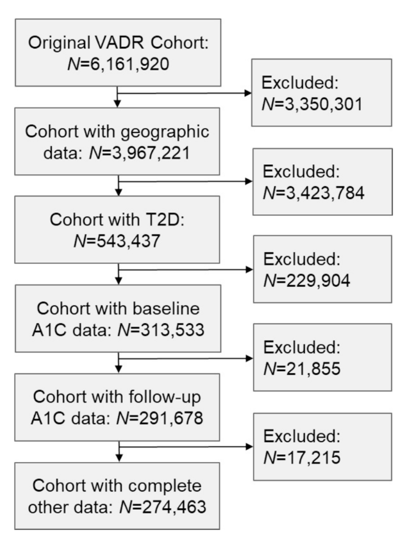

Fig. 1. Flow Chart of the Analytic Sample of United States Veterans with a New Type-2 Diabetes Diagnoses in 2008–2018. ([1] VADR = Veteran's Administration Diabetes Risk, [2] T2D = Type 2 Diabetes, [3] A1C = glycated hemoglobin, an indicator of glycemic control).

Programming Interface for Python™. Then, two LTPA environmental exposure variables were assigned to the patient's census tract: park proximity and physical activity facility density. We drew from definitions established in the Retail Environment and Cardiovascular Disease (RECVD) dataset. *Park proximity* was defined as the distance to the nearest seven parks from a census tract's population-weighted centroid. Parks included national (2 %), state (7 %), and local (91 %) parks obtained from the Centers for Disease Control and Prevention and originally sourced from the Homeland Security Infrastructure Program Gold 2011 database and 2010 Esri ArcGIS 10.1 data (Wen et al., 2013). The measure considers a census block's spatial access probability to its nearest seven parks, weighted by block population, and aggregated to the census-tract level (Zhang et al., 2011). The measure is strongly correlated with Euclidean distance to the closest one, five, and nine parks in a given tract and avoids arbitrarily drawing fixed boundaries of exposure (Zhang et al., 2011). *Physical activity facility density* was defined as the five-year average density (count per km^2) of facilities within a network buffer around the population-weighted centroid of a census tract. Facilities were sourced from the National Establishment Time Series database of multi-use establishments and included fitness facilities, gyms, athletics and sports clubs, instructional studios, and recreation centers. We assigned facilities data that were collected from 2007 to 2015 and averaged within the five years immediately preceding a patient's T2D diagnosis. Walking and driving network buffers were defined using Esri ArcGIS StreetMap Premium™ 2019 street network data with standard precision and default settings. We applied different street network distances to walking and driving network buffers based on four *community types*: higher density urban, low-density urban, suburban/small town and rural. These classifications were based on a modified version of Rural-Urban Commuting Area codes applied at the census-tract level (McAlexander et al., 2022). We assigned network buffers of exposure to physical activity facility density reflecting travel distances appropriate to each community type: one-mile walking buffer for high-density urban, two-mile driving buffer for low-density urban, six-mile driving buffer for suburban/small town, and 10-mile driving buffer for rural communities. These buffers reflect an average of 10–15 min that adults may be willing to travel to access recreation (Hurvitz et al., 2014; Yang and Diez-Roux, 2012). Physical activity facility counts were divided by the corresponding area in km^2 within the relevant buffer.

2.3. A1C at baseline

We defined baseline A1C as the closest recorded A1C value to the date of new T2D diagnosis that was within 30 days prior to or after this date. We considered severity of baseline A1C low if less than 7.0 %, moderate if 7.0 % to 8.9 %, and severe if 9.0 % or greater (ADA, 2021).

2.4. Glycemic control outcomes

The primary outcome was a repeated-measures binary variable indicating whether the results of A1C tests administered more than 30 days after T2D diagnosis were considered to fall within a clinically therapeutic range, where 1 = in-range and 0 = not-in-range. Based on clinical guidelines (which differ slightly based on age and other chronic illness) (ADA, 2021; Conlin et al., n.d.; Qaseem et al., n.d.), we defined "in-range" as A1C test values of 5.0 % to 6.9 % for patients less than 80 years old and 5.0 % to 8.5 % for patients 80 years or older. We included all available, non-duplicate A1C tests during the follow-up period. We defined a secondary measure of T2D control as the proportion of tests considered in-range (tests in-range/total follow-up tests). We operationalized this outcome as all tests in-range = 1 and anything fewer = 0.

2.5. Statistical analysis

We conducted descriptive analyses to summarize demographic and health-related characteristics and distributions of physical activity facility density and park distance variables across four community types (see Table 1). We also summarized the mean number of A1C follow-up tests per patient, stratified by severity of baseline A1C and proportion of A1C tests in-range (see Table 2). To examine associations between the LTPA environment and odds of glycemic control, we used generalized estimating equations (GEE) with a logit link function for repeated binary dependent variables (Ballinger, 2004; Parzen et al., 2011). When determining the need for a multilevel modeling approach to account for clustering at the county level, an intraclass correlation coefficient of 0.004 indicated that nesting of an average of 692 individuals per county across 392 counties accounted for a negligible amount of the total variance in the proportion of A1C tests in-range. We specified an exchangeable working correlation matrix to account for the dependency among within-individual repeated A1C follow-up measures over time. We preferred a GEE marginal model to maximum likelihood estimation in order to interpret parameter estimates in terms of population-averaged change in A1C due to differential, time-invariant access to physical activity facilities and parks across a large number of neighborhoods (Hubbard et al., 2010). GEE is also robust to unequal numbers of A1C follow-up measures across individuals, allowing for flexibility in the number of follow-up measures per participant. We included a time-varying covariate of years since T2D diagnosis to account for the timing of each test in relation to diabetes progression. We examined physical activity facility density and park proximity exposures in separate statistical models with and without adjusting for the other, and then exponentiated regression coefficients prior to interpretation. To demonstrate associations between LTPA environmental exposures and proportion of A1C tests in-range among Veterans with a new T2D diagnosis, we used binomial logistic regression to examine associations between each exposure and these outcomes.

At the individual-level, we also adjusted for baseline 1) A1C, 2) comorbid medical conditions assessed using the Elixhauser Comorbidity Index with Swiss weightings of −7 to 17 to yield possible index scores of −13 to 34 where lower scores indicate lower risk of mortality (Sharma et al., 2021), 3) age at VADR cohort entry, 4) sex (male or female), 5) non-Hispanic race and Hispanic ethnicity (Hispanic, non-Hispanic white, non-Hispanic black, non-Hispanic Asian, non-Hispanic American Indian/Alaska native, non-Hispanic native Hawaiian/other Pacific Islander, and missing), 6) low-income/disability flag (based on a patient's priority group for Veteran benefits), and 7) marital status (married or living with partner, single, and missing). Indicator variables were created and included in statistical models to account for missing race/ethnicity (6.7 %), income/disability (0.8 %), and marital status (6.4 %).

At the census tract-level, we adjusted for percent Hispanic and percent non-Hispanic black residents and the following variables from the RECVD study: 1) neighborhood socioeconomic environment, a continuous z-score sum of the percent of adults with less than a high school education, unemployed, and households with <$30,000 annual income, in poverty, on public assistance, and without a car (higher score indicating higher disadvantage) (Yang et al., 2014), and 2) land use environment, created based on average block length, average block size, household density, intersection density, street connectivity, retail establishment density, and percent of developed land. Finally, we examined potential moderation by continuous neighborhood socioeconomic environment by including interaction terms in the GEE models with each physical activity facility density and park distance, which were mean-centered prior to analysis. We stratified all models by community type, using Python 3 with the "GENMOD" GEE package and SAS 9.4 to conduct the analyses.

Table 1
Descriptive statistics of baseline individual- and neighborhood-level characteristics among United States veterans with a new type-2 diabetes diagnoses in 2008–2018.

	All community types (N = 274,463)		High-density urban (N = 32,649)		Low-density urban (N = 98,087)		Suburban/small town (N = 59,727)		Rural (N = 84,000)	
	n/mean	%/SD	n/mean	%/SD	n/mean	%/SD	n/mean	%/SD	n/mean	%/SD
Individual-level variables										
Age at cohort entry	60.5	11.8	58.9	11.8	60.1	12.1	60.7	12.0	61.5	11.3
Age at new diabetes diagnosis	64.1	11.7	62.5	11.7	63.6	12.0	64.2	11.9	65.1	11.2
Age categories										
18–39	13,192	4.8	18,08	5.5	5195	5.3	2914	4.9	3275	3.9
40–59	102,669	37.4	14,498	44.4	38,506	39.3	21,681	36.3	27,984	33.3
60–79	143,020	52.1	14,719	45.1	48,488	49.4	31,602	52.9	48,211	57.4
80+	15,582	5.7	1624	5.0	5898	6.0	3530	5.9	4530	5.4
Sex										
Male	260,793	95.0	30,777	94.3	92,535	94.3	56,704	94.9	80,777	96.2
Female	13,670	5.0	1872	5.7	5552	5.7	3023	5.1	3223	3.8
Race/ethnicity[1,2]										
White	183,698	66.9	14,001	42.9	59,315	60.5	42,832	71.7	67,550	80.4
Black	53,758	19.6	12,322	37.7	24,107	24.6	9514	15.9	7815	9.3
Hispanic	12,852	4.7	3007	9.2	5813	5.9	2385	4.0	1647	2.0
Asian	2337	0.9	745	2.3	1040	1.1	392	0.7	160	0.2
Native Hawaiian/Pacific islander	1728	0.6	269	0.8	726	0.7	367	0.6	366	0.4
American Indian/Alaska native	1599	0.6	158	0.5	454	0.5	332	0.6	655	0.8
Income/disability[1]										
Disabled	98,945	36.1	10,532	32.3	36,589	37.3	22,785	38.2	29,039	34.6
Low income	104,553	38.1	15,849	48.5	37,687	38.4	20,569	34.4	30,448	36.3
None of the above	68,681	25.0	5949	18.2	22,995	23.4	15,892	26.6	23,845	28.4
Marital status[1]										
Married or living with a partner	154,187	56.2	12,873	39.4	52,069	53.1	36,379	60.9	52,866	62.9
Single	102,615	37.4	15,793	48.4	38,891	39.7	20,182	33.8	26,686	31.8
Elixhauser comorbidities index	−0.4	10.6	−0.3	11.5	−0.5	10.8	−0.6	10.3	−0.3	10.3
Baseline A1C[3] (± 30 days of diagnosis)	7.2	1.8	7.4	2.0	7.2	1.8	7.1	1.7	7.1	1.6
Baseline A1C[3] severity										
< 7.0 %	173,367	63.2	19,761	60.5	61,757	63.0	38,051	63.7	53,798	64.1
7.0–8.9 %	69,544	25.3	8098	24.8	24,336	24.8	15,232	25.5	21,878	26.1
≥ 9.0 %	31,552	11.5	4790	14.7	11,994	12.2	6444	10.8	8324	9.9
Number of A1C[3] follow-up tests per patient	11.7	7.7	12.0	7.9	11.6	7.7	11.6	7.6	11.8	7.6
Proportion of patient's A1C[3] follow-up tests in-range	0.7	0.3	0.7	0.4	0.7	0.3	0.7	0.3	0.7	0.3
Neighborhood-level variables										
Physical activity facility density in street network buffer[4]	0.7	1.3	2.1	3.1	0.9	0.7	0.3	0.3	0.1	0.1
Population-weighted distance to the closest seven parks[4]	3.4	4.3	0.6	0.6	1.3	1.4	2.9	2.9	7.3	5.3
Neighborhood socioeconomic environment[5]	17.5	10.2	26.2	13.7	13.1	8.1	16.1	9.3	20.3	8.0
Land use environment[4]	0.0	0.9	0.0	0.8	0.0	0.9	−0.1	0.9	0.1	0.9
Percent Hispanic[5]	0.1	0.2	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1
Percent non-Hispanic Black[5]	0.2	0.2	0.3	0.3	0.2	0.3	0.1	0.2	0.1	0.2

1 Does not list 6.74 % missing for race/ethnicity, 0.83 % missing for income/disability, and 6.43 % missing for marital status.
2 All race/ethnicity categories except Hispanic are non-Hispanic.
3 A1C = glycated hemoglobin, an indicator of glycemic control.
4 Geographic information systems-based measure.
5 United States census-derived measure aggregated within census tract.

Table 2
Mean (SD) number of A1C[1] follow-up tests by baseline A1C severity and glycemic control among United States veterans with a new type-2 diabetes diagnosis in 2008–2018.

	Baseline A1C[1] severity		
	< 7.0 % *M* (*SD*)	7.0 to 8.9 % *M* (*SD*)	≥ 9.0 % *M* (*SD*)
Proportion of A1C[1]			
Follow-up tests in-range			
Less than 0.25	14.1 (9.3)	14.3 (9.3)	15.0 (9.7)
0.25 to 0.49	13.6 (8.5)	13.7 (8.4)	14.8 (8.8)
0.50 to 0.74	13.1 (7.4)	13.3 (7.4)	13.9 (7.7)
0.75 to 1.00	9.6 (6.1)	10.3 (6.6)	11.4 (6.8)

1 A1C = glycated hemoglobin, an indicator of glycemic control.

3. Results

3.1. Descriptive analyses

The analytic sample included 274,463 Veterans who were newly diagnosed with T2D during the study period. The majority were male (95.0 %) and identified as non-Hispanic white (66.9 %). Patients were 64.0 ± 11.7 years of age upon receiving a new T2D diagnosis. About 36 % were disabled (irrespective of income), 38 % were not disabled but were low-income, and 25 % were neither. Patients' mean baseline A1C was 7.2 % ± 1.8 %, descending from a high of 7.4 % ± 2.0 % in high-density urban to a low of 7.1 % ± 1.6 % in rural communities. Patients' mean number of A1C follow-up tests (11.7 ± 7.7) and mean proportion of patients' A1C follow-up tests that were considered in-range (0.69 ± 0.34) were also relatively uniform across community types. As shown in Table 2, patients with at least 75 % of their A1C follow-up tests in range had slightly fewer follow-up tests on average. The average density of physical activity facilities within network buffers was 2.1 ± 3.1 facilities per km^2 in high-density urban, 0.9 ± 0.7 in low-density urban, 0.3 ± 0.3 in suburban/small town, and 0.1 ± 0.1 in rural communities. The average distance to the nearest seven parks was 0.6 ± 0.6, 1.3 ± 1.4, 2.9 ± 2.9, and 7.3 ± 5.3 miles for each community type, respectively.

3.2. Odds of repeated A1C tests in-range

As shown in Table 3, in high- and low- density urban communities (but not in suburban/small town and rural), a one-facility per km^2 greater physical activity density within a patient's network buffer was associated with 1.01 and 1.03 times greater odds of in-range A1C tests during follow-up, respectively. That is, high density urban-dwelling patients were 1 % more likely, and low density urban-dwelling patients were 3 % more likely, to have in-range A1C tests, controlling for time since new T2D diagnosis, if they had access to an additional physical activity facility. Across community types, farther distance to travel to the nearest seven parks was not associated with lesser odds of in-range A1C tests during follow-up. Unexpectedly, in low-density urban communities, odds of in-range A1C tests were diminutively greater at farther park distances. Tests of moderation by neighborhood socioeconomic environment were not significant in models for either physical activity facility density or park distance in any community type (all 95 % confidence intervals for the adjusted odds ratio for each interaction term were inclusive of 1.00).

3.3. Odds of all A1C tests in-range

Also shown in Table 3, in low-density urban communities only, patients with a one-facility per km^2 greater physical activity density within their network buffer were more likely to have all A1C follow-up tests in-range as compared to having at least one follow-up test that was not in-range. That is, low-density urban residents were 4 % more likely to maintain glycemic control if they had access to an additional physical activity facility. Similarly to the first modeling approach, low-density urban residents who had one mile farther to travel to parks were 2 % more likely to have all A1C follow-up tests in-range as compared to having at least one test not in-range.

Table 3
Odds of in-range A1C[1] follow-up tests associated with physical activity facility density and park distance among United States veterans with a new type-2 diabetes diagnosis in 2008–2018 by urbanicity, examined using two statistical modeling approaches.

	Odds of all A1C[1] follow-up tests in-range		Odds of repeated A1C[1] follow-up tests in-range	
	Adjusted Odds Ratios[2]	95 % confidence intervals	Adjusted Odds Ratios[3]	95 % confidence intervals
Density of physical activity facilities				
High density urban	1.00	1.00, 1.02	1.01*	1.00, 1.01
Low density urban	1.04*	1.01, 1.07	1.03*	1.01, 1.04
Suburban/ small town	1.06	0.99, 1.14	1.02	0.97, 1.08
Rural	1.19	0.93, 1.54	1.08	0.90, 1.29
Distance to seven closest parks				
High density urban	1.02	0.98, 1.07	1.00	0.97, 1.03
Low density urban	1.02*	1.01, 1.03	1.01*	1.00, 1.02
Suburban/ small town	1.00	1.00, 1.01	1.00	1.00, 1.01
Rural	1.00	0.98, 1.00	1.00	1.00, 1.00

[1] A1C = glycated hemoglobin, an indicator of glycemic control.
[2] Logistic regression used to model odds of all A1C follow-up tests in-range vs. less than all tests in-range with an asterisk indicating significance. All logistic regression models controlled for baseline A1C, age at diabetes diagnosis, sex, race/ethnicity, income/disability, marital status, comorbidities, and neighborhood-level socioeconomic status, land use mix, % black, and % Hispanic.
[3] Generalized estimating equations (GEE) used to model odds of repeated A1C follow-up tests in-range vs. not-in-range with an asterisk indicating significance. All GEE models also controlled for time of A1C test in years since new type-2 diabetes diagnosis.

4. Discussion

In United States Veterans with T2D, greater access to physical activity facilities and parks did not seem sufficient to promote better glycemic control after diagnosis. Few prior studies have considered these associations longitudinally or differences in these associations by community type. Our findings suggest that high- and low-density urban communities may experience a small benefit from access to physical activity facilities compared to no clear benefit in less urbanized communities. That is, physical activity facility density scores were associated with a 1.01 and 1.03 times greater odds of in-range A1C tests during follow-up, and only in high- and low-density urban communities, while associations were null in suburban/small town and rural communities and did not vary significantly by level of socioeconomic disadvantage. Results of fully adjusted models compared to models that adjusted only for individual-level covariates suggest that neighborhood-level characteristics accounted for negligible additional variance or may relate in complex ways to individual-level covariates (Trinidad et al., 2022). In a 2015–2018 cohort of primary care patients, living in urban areas with lower availability of physical activity facilities was associated with a greater risk of T2D and complications; however, associations were strongest in areas with higher socioeconomic disadvantage (Cereijo et al., 2023). In prior multicohort studies, higher socioeconomic disadvantage was associated with higher risk of T2D (Uddin et al., 2023), and these associations via physical activity facility density may strengthen across increasing quartiles of disadvantage (Moon et al., 2023).

Effects of distance to the closest seven parks on odds of glycemic control were largely null across community types. Unexpectedly, in low-density urban areas, odds of in-range A1C tests were diminutively greater with farther park distances. Low-density urban communities had relatively lower mean neighborhood socioeconomic disadvantage than the other community types. Perhaps fewer residents in these communities rely on low-cost options for recreation such as public parks (Cereijo et al., 2023). Few studies have examined distance to parks and T2D, however exposures such as greenspace have been associated with lower T2D risk (Twohig-Bennett and Jones, 2018). Notably, among 260 newly diagnosed T2D patients in an urban Australian community, greenspace within residential buffers was not associated with changes in physical activity over the three-year study period (Chong et al., 2019). The measure of spatial access to parks used in the current study might not be sufficient to capture what bolsters physical activity levels in T2D patients to the extent needed to manage glycaemia as hypothesized. Despite the plausibility of these associations, geographic information systems-based measures of LTPA facilities and parks might not be as strongly associated with LTPA behavior, and therefore with glycemic control, as are survey-based measures that account for factors such as quality, affordability, and perceived convenience (Orstad et al., 2016).

Limitations and strengths. To minimize temporality bias, environmental exposures were assigned at the time of T2D diagnosis; however, we could not account for potential changes in environmental attributes throughout the follow-up period that might have influenced the observed associations. Residential relocation during the study period could also change the exposure, which was partially accounted for by excluding those who changed states for clinical care during the study period. We could not address possible bias from residential self-selection. Buffer sizes may not reflect an individual's most relevant neighborhood context. Physical activity and healthy eating data were not available and should be considered in future studies. Fast-food restaurant and supermarket densities have been associated with higher and lower T2D risk, respectively, in the VADR cohort (Kanchi et al., 2021). Medical records provide data on verified illnesses but may be inaccurate or incomplete. There may have been unmeasured illness and treatment effects during follow-up (e.g., undiagnosed T2D, medication use, or program participation). However, because this patient population had access to Veterans Affairs healthcare, we anticipated robust diagnosis, testing, and treatment rates that were not geographically distributed, and therefore unrelated to the exposure variables. Considering patients may begin new treatments during follow-up, treatment could be examined in future studies as an exposure of interest in relation to glycemic control, potentially modified by the LTPA environment.

Participants who remained in the study over time may differ characteristically (e.g., have better health or higher income) from participants who were deceased or discontinued care. Generalizability may also be limited beyond non-male, non-white populations whose monitoring of A1C is not well documented in an electronic health record. The exclusion of 229,904 patients with T2D without A1C data at baseline may not limit generalizability considerably because they were comparable in demographics and neighborhood-level characteristics to those in the final analytic sample, though they were on average three years older when diagnosed (67.2 $\pm$ 12.3), and slightly more were non-Hispanic white (74.4 %) and low-income (41.5 %). Strengths of this study include its large nationwide sample, a decade-long longitudinal design, multiple repeated A1C follow-up measures, utilization of geographic information systems-based measures, control for confounding at the individual- and neighborhood-level, and comparisons across the urban-rural continuum.

Associations between the LTPA environment, physical activity behavior, and chronic disease management are highly complex, and likely differ based on local contexts, cultures, and population demographics (Gidlow et al., 2019). Broader access to neighborhood physical activity facilities may contribute in small ways to maintaining glycemic control in urban populations with newly diagnosed T2D. Research is needed that examines the interplay between individual, socioeconomic and physical neighborhood environments and TD2 outcomes (Schüle and Bolte, 2015). Our understanding of the appropriate geographies to examine and their associations with physical activity behavior and glycemic control is particularly limited in suburban/small town and rural communities. Ultimately, future studies should identify optimal typologies of built, natural, physical activity, and food environmental supports that contribute to the effectiveness of chronic disease management interventions across diverse geographies and communities. Research is also needed to evaluate interventions that increase access to and promote the use of LTPA facilities and parks, while tailoring interventions to local communities.

CRediT authorship contribution statement

Stephanie L. Orstad: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Priscilla M. D'antico:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Data curation, Conceptualization. **Samrachana Adhikari:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Rania Kanchi:** Writing – review & editing, Project administration, Investigation, Data curation. **David C. Lee:** Writing – review & editing, Conceptualization. **Mark D. Schwartz:** Writing – review & editing, Supervision, Resources, Methodology. **Sanja Avramovic:** Writing – review & editing, Investigation, Data curation. **Farrokh Alemi:** Writing – review & editing, Methodology, Investigation. **Brian Elbel:** Writing – review & editing, Funding acquisition, Conceptualization. **Lorna E. Thorpe:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Deidentified study data are available upon reasonable request to researchers who provide a methodologically sound proposal and agree to the requirements of a data use agreement.

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