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Ekaterina Lyulina[1], Gulsara Asatova[2], Nargiz Matkarimova[3], Gulmira Ismagulova[3], Lesia Korobeynikova[4]

MOVEMENT TRANSITION AND ADULT OBESITY: PHYSICAL INACTIVITY, DIGITALISATION AND DEVIATIONS FROM GDP-BASED BENCHMARKS IN A GLOBAL PANEL, 2000-2022

[1]Department of Martial Arts, Uzbek State University of Physical Education and Sport, Chirchik, Uzbekistan
[2]Graduate Studies Office, Uzbek State University of Physical Education and Sport, Uzbekistan
[3]Department of Management, Uzbek State University of Physical Education and Sport, Uzbekistan
[4]Department of Combat Sport, National University of Ukraine on Physical Education and Sport, Kyiv, Ukraine

ABSTRACT

INTRODUCTION. Adult obesity and insufficient physical activity co-evolve with economic development, urbanisation and digitalisation, which complicates interpretation of country-level associations.

PURPOSE. To examine whether within-country changes in insufficient physical activity were associated with adult obesity after accounting for internet penetration and other structural factors, whether internet penetration remained associated with obesity, and whether deviations from common GDP/year benchmarks co-varied.

MATERIAL AND METHODS. An unbalanced ecological panel included 2,707 country-year observations from 164 countries during 2000-2022. Two-way fixed-effects linear models with country- clustered standard errors estimated associations with adult obesity after adjustment for internet use, log GDP per capita, dietary energy supply, unemployment, urbanisation, population ageing, secondary enrolment and services employment. Obesity and inactivity benchmark residuals were defined as observed minus values predicted by log GDP per capita and year effects. Sensitivity analyses added health expenditure, excluded countries with fewer than five observations and decomposed the residual association into between-country and within-country components.

RESULTS. Insufficient physical activity was positively associated with obesity ($\beta=0.174$, $SE=0.041$, $p<0.001$); internet use also remained positively associated ($\beta=0.037$, $SE=0.010$, $p<0.001$). The inactivity benchmark residual was associated with the obesity benchmark residual in the fixed-effects model ($\beta=0.163$, $SE=0.045$, $p<0.001$), with similar estimates after health-expenditure adjustment ($\beta=0.164$) and restriction to countries with at least five observations ($\beta=0.162$). The unadjusted between-country and within-country components were both positive ($\beta=0.285$ and $\beta=0.189$, respectively; both $p<0.001$).

CONCLUSIONS. Within countries, higher insufficient physical activity and higher internet use were associated with higher adult obesity. Country-years above the GDP/year benchmark for inactivity also tended to be above the corresponding obesity benchmark. These ecological results are associational; the residuals are model-dependent descriptive diagnostics, not validated indices or causal estimates.

Keywords: *obesity, physical inactivity, digitalization, ecological studies, panel data*

INTRODUCTION

Adult obesity and insufficient physical activity are major population-health concerns. Adult obesity is commonly defined as body mass index (BMI) of at least 30 kg/m², while insufficient physical activity indicates failure to meet recommended activity levels (1-4). Global surveillance shows that obesity prevalence has risen markedly and that insufficient physical activity increased between 2000 and 2022 (2,3,5).

Obesity reflects interacting biological, dietary, social, economic and environmental influences (6-8). In this study, the term movement transition is used as a macro-level framing for concurrent changes in the opportunities and demands for everyday movement that accompany economic development, urbanisation, occupational change and digitalisation. It is not a directly measured latent construct or a validated country index. Digitalisation is operationalised as the percentage of the population using the internet; this is treated as a broad structural marker of digital penetration rather than an individual measure of screen time, sedentary behaviour or use of digital food services.

Physical inactivity, digitalisation and obesity can be viewed within broader socioeconomic and environmental transitions. Economic growth is associated with changes in occupational and transport- related physical activity and sedentary behaviour, although reported patterns vary across settings (9). Digitalisation is also reshaping food access and retail. A recent scoping review identified multiple pathways through which digital food retail environments may influence health (10), while a 97-country analysis documented increasing digital grocery sales and broader changes in food retail environments that were positively correlated with obesity prevalence (11). These processes occur alongside urbanisation, demographic change and shifts in food systems that may influence obesity through multiple pathways (6-8,11). Considering physical inactivity and digitalisation within the same ecological framework may therefore help characterise how these structural changes co-vary with obesity at population level.

Country-level evidence on the inactivity-obesity relationship remains limited. An early 76-country analysis found that physical inactivity prevalence was higher in wealthier, more urbanised countries when benchmarked against the Human Development Index (12), and a subsequent global surveillance report described substantial cross-country variation in adult physical activity levels without a systematic development-adjusted comparison with obesity (13). Neither study benchmarked inactivity and obesity jointly against a common development indicator or separated within-country change from persistent cross-country differences.

A raw cross-country association may reflect stable national differences rather than change occurring within countries. It may also reflect a common development pathway rather than a direct effect of inactivity on obesity. The present study addresses this problem with country and year fixed effects (FE) and with transparent GDP (Gross Domestic Product)/year benchmark residuals. The Movement Gap is observed insufficient physical activity minus the value predicted by log GDP per capita and year effects; the Obesity Gap is defined analogously. Positive values indicate outcomes above the chosen benchmark. These residuals are model-dependent diagnostics, not validated indices or measures of policy performance.

From a population-surveillance perspective, benchmarking may help distinguish country-years that deviate from broad development-related patterns. A country-year with both inactivity and obesity above their GDP/year predictions may warrant closer examination of movement environments, food systems, socioeconomic conditions or measurement, whereas discordant deviations may point toward alternative explanations. These residual patterns are descriptive and should not be interpreted as causal effects or country rankings.

The study therefore addressed three linked questions: whether adult insufficient physical activity was associated with adult obesity within countries over time after adjustment for internet penetration and other structural covariates; whether internet penetration remained associated with obesity in the same within-country framework; and whether country-years above the inactivity benchmark were also above the obesity benchmark, including in a between-within decomposition designed to assess concern about shared construction of the modelled source series.

MATERIAL AND METHODS

Study design and sample. A longitudinal ecological panel design was used, with the country-year as the unit of analysis. The study covered 2000-2022. All countries available in the harmonised repositories were eligible. Complete-case selection for the main specification produced 2,707 observations from 164 countries. The panel was unbalanced because indicator coverage varied. Missing values were handled by listwise deletion; no additional imputation was performed.

Country contributions ranged from 1 to 23 annual observations (mean 16.5). Of the 164 countries, 150 contributed at least five observations, accounting for 2,661 of the 2,707 country-years; the remaining 14 countries contributed 46 observations. This uneven coverage reflects complete-case availability across the indicators rather than a sampling design. The analytical

sample should therefore be interpreted as a data-available global panel rather than a probability sample of all countries or years.

Data sources and variables. Adult obesity prevalence was the percentage of adults aged 18 years or older with BMI at least 30 kg/m², based on modelled estimates accessed through Our World in Data (5,14). Adult insufficient physical activity was the percentage of adults not meeting recommended levels, based on harmonised global estimates (2). The obesity model does not use physical activity as an input, whereas the inactivity modelling series includes adult obesity among its time-varying covariates (2,5); this asymmetry motivated the between-within analysis described below.

GDP per capita in purchasing-power-parity terms, internet use, unemployment, urban population share, population aged 65 years and older, gross secondary-school enrolment, services employment and current health expenditure were obtained from World Development Indicators (15). Dietary energy supply in kilocalories per capita per day was obtained from FAOSTAT Food Balances (16). GDP was log-transformed. Dietary energy supply represents national food availability rather than individual intake.

Statistical analysis. Two-way fixed-effects linear regressions included country and year effects and country-clustered standard errors. Country effects absorb time-invariant national characteristics; year effects absorb shocks and trends common to countries (17,18). Model 1 excluded inactivity. Model 2 added inactivity and was the primary model. Model 3 added health expenditure. Model 4 added an exploratory internet-by-inactivity interaction. Coefficients are percentage-point changes in adult obesity associated with a one- unit increase in each predictor, holding the remaining covariates constant.

Fixed versus random effects was assessed with a conventional Hausman test and a cluster-robust Mundlak test (19,20). Collinearity was examined with pooled and approximate within-transformed variance inflation factors (VIFs). A one-year-lagged inactivity model assessed temporal ordering; it does not remove reverse causality or time-varying confounding.

GDP/year benchmark residuals and shared-construction check. Adult obesity and adult insufficient physical activity were each regressed on log GDP per capita and year effects in the pooled country-year sample. The Obesity Gap and Movement Gap were the respective observed-minus-predicted residuals. The primary residual model regressed Obesity Gap on Movement Gap, internet use, dietary energy supply, unemployment, urbanisation, population ageing, secondary enrolment, services employment, country effects and year effects. Stability analyses added health expenditure and restricted the sample to countries contributing at least five observations.

To examine whether the gap association was mainly a consequence of persistent country-level anchoring in the modelled source series, Movement Gap was decomposed into the country mean (between-country component) and the year-specific deviation from that mean (within-country component). Both were entered simultaneously in an unadjusted model; the primary fixed-effects residual model provides the adjusted within-country estimate. A predominantly artifactual association would be expected to weaken substantially in the within-country component.

Country profiles, reporting and ethics. For descriptive interpretation, countries with at least five observations were assigned to four profiles using zero as the pre-specified threshold: both gaps below zero; both at or above zero; positive Movement Gap with negative Obesity Gap; or negative Movement Gap with positive Obesity Gap. No uncertainty interval was assigned to individual classifications, and countries close to zero may change category under another benchmark.

Reporting followed STROBE principles adapted to an ecological panel design (21,22). Analyses were conducted in Stata 14 (StataCorp LP, College Station, TX, USA) with two-sided $p<0.05$ (23). Only publicly available aggregate country-level data were used; ethics approval and informed consent were therefore not applicable.

RESULTS

Descriptive findings. The main sample contained 2,707 country-year observations from 164 countries. Mean adult obesity prevalence was 17.72%, mean insufficient physical activity was 26.61%, mean internet use was 40.99%, and mean dietary energy supply was 2,897 kcal per capita per day (Table 1).

Fixed-effects estimates and diagnostics. In Model 1, internet use was positively associated with adult obesity ($\beta=0.054$, SE=0.009, $p<0.001$). In the primary model, insufficient physical activity was positively associated with obesity ($\beta=0.174$, SE=0.041, $p<0.001$), while internet use remained positive ($\beta=0.037$, SE=0.010, $p<0.001$). The smaller internet coefficient after inactivity was added is compatible with overlapping pathways but is not a mediation estimate. Adding health expenditure produced nearly identical estimates. The internet-by-inactivity interaction was not statistically significant (Table 2).

The cluster-robust Mundlak test rejected the random-effects specification ($\chi^2(9)=61.75$, $p<0.001$), supporting fixed effects. Pooled VIFs were higher for development variables, but the maximum approximate within-transformed VIF was 2.85 and the mean was 1.58. In the available one-year-lagged specification, inactivity remained positive ($\beta=0.174$, $p<0.001$).

GDP/year benchmark residuals. The two residuals were centred near zero by construction and were positively correlated (r=0.340). In the primary fixed-effects residual model, Movement Gap was positively associated with Obesity Gap (β=0.163, SE=0.045, p<0.001). Estimates were similar after adding health expenditure (β=0.164, SE=0.046) and after excluding countries with fewer than five observations (β=0.162, SE=0.045) (Table 3).

The unadjusted between-country component was β=0.285 (SE=0.059, p<0.001), and the unadjusted within-country component was β=0.189 (SE=0.047, p<0.001). The adjusted fixed-effects estimate for within-country variation was β=0.163 (SE=0.045, p<0.001). The within-country association was therefore not weaker than expected under a pattern driven primarily by stable country-level anchoring, although shared modelling cannot be ruled out completely.

Among 150 countries with at least five observations, 53 were classified with both gaps below zero, 38 with both gaps at or above zero, 28 with positive Movement Gap and negative Obesity Gap, and 31 with negative Movement Gap and positive Obesity Gap. Figure 1 displays observation-level heterogeneity. These classifications are exploratory and should not be interpreted as rankings.

DISCUSSION

Principal findings. Within countries over time, higher insufficient physical activity was associated with higher adult obesity after adjustment for internet use, income, dietary energy supply, unemployment, urbanisation, ageing, education, services employment and common year effects. Country-years with inactivity above the GDP/year prediction also tended to have obesity above the corresponding prediction. The residual coefficient was stable after health-expenditure adjustment and sample restriction.

These findings extend earlier country-level evidence. Dumith et al. (12) linked physical inactivity prevalence to national development status using a cross-sectional comparison against the Human Development Index, and Hallal et al. (13) described substantial global variation in activity levels without linking that variation systematically to obesity. Neither study distinguished within-country change from persistent cross-country differences nor benchmarked obesity and inactivity jointly against a common development indicator. The present analysis addresses those design gaps, but it remains ecological and should not be interpreted as evidence that changing inactivity in an individual would produce the estimated change in obesity.

The two harmonised outcome series are not fully independent by construction. The physical inactivity estimates (2) incorporate adult obesity prevalence as a country-specific,

time-varying covariate in their Bayesian hierarchical model, whereas the obesity series (5) does not use inactivity as an input. If the residual association were driven mainly by stable country-level anchoring from this shared construction, it would be expected to weaken substantially in the within-country component. Instead, the within-country component remained positive and of similar order to the between-country component. This reduces, but does not eliminate, concern about shared construction because the obesity covariate in the inactivity model varies over time.

The positive global inactivity-obesity association should not be treated as universal across settings. In a 2025 ecological panel of ten Eastern European countries using country and year fixed effects, Siminiuc et al. found strong associations for dietary energy and fibre but no statistically significant association between insufficient physical activity and obesity (24). That result contrasts with the positive coefficient in the present 164-country panel. The discrepancy is not necessarily a contradiction: geographic scope, available within-country variation, covariate specification and measurement differ between the studies. It does, however, argue against presenting a single ecological coefficient as a context-free structural effect.

The digitalisation finding also requires a distinction between individual behaviour and national structural penetration. A 2025 meta-analysis of 393,743 women from 36 low- and middle-income countries reported positive associations of mobile-phone and television use with overweight or obesity (25). Reviews of the digital food retail environment identify plausible pathways through food purchasing, delivery and eating behaviour while emphasising that the evidence base remains heterogeneous (10,26). A recent 97-country analysis also documented increasing digital grocery sales and broader retail changes that were positively correlated with obesity prevalence (11). These studies make screen-related and food-retail mechanisms plausible, but they do not show that the present internet coefficient measures those mechanisms. National internet penetration may also capture occupational restructuring, service-sector growth, remote work, access to services and other correlated changes; it should therefore not be labelled a direct digital effect.

Recent built-environment reviews similarly support a contextual rather than deterministic interpretation. Zhang et al. found that associations between built-environment characteristics and physical activity vary across age groups and are not uniformly consistent (27). Nigg et al. reported that destination accessibility, connectivity, walking and cycling infrastructure, safety and aesthetics were among the attributes most often positively associated with adult physical activity in tropical and subtropical settings, while also noting limited evidence from non-Western contexts (28). A systematic review of natural environments and

obesity further indicates that environmental pathways may extend beyond movement alone (29). Together, this literature supports attention to movement environments, but it does not identify which environmental feature explains a positive Movement Gap in any specific country.

The coefficient for insufficient physical activity should be interpreted at population level. A one-percentage-point increase in national insufficient activity was associated with an estimated 0.174-percentage-point increase in obesity within countries, conditional on the model. This is an association, not an individual dose-response effect.

Internet use remained associated with obesity after inactivity was added. The smaller internet coefficient after inactivity entered the model is compatible with overlapping pathways but is not a mediation estimate. The null internet-by-inactivity interaction provides no evidence that the internet- obesity association varied systematically across national inactivity levels.

The negative coefficients for urbanisation and population ageing in the fixed-effects model should not be read as claims that urbanisation or ageing protects individuals. Fixed-effects coefficients describe how changes within a country co-varied after adjustment; they may differ from cross-sectional gradients and remain vulnerable to omitted time-varying factors.

The high within R^2 values should likewise not be interpreted as evidence that the measured covariates alone strongly predict obesity. In a two-way fixed-effects model, country and year effects absorb substantial stable cross-country heterogeneity and common temporal change. The more relevant evidence for the focal associations is the magnitude, precision and stability of the inactivity and internet coefficients across specifications.

Public health relevance. Physical activity policy should address environments as well as individual advice. Movement supportive urban design, safe walking and cycling routes, public-transport integration, access to recreation, school physical education and workplace movement opportunities are established policy domains, although the strength of specific built-environment associations varies by context (28,30). A positive Movement Gap together with a positive Obesity Gap may identify settings where movement environments merit closer surveillance; discordant gaps may direct attention toward food-system, socioeconomic or measurement explanations. The framework is a triage aid and does not replace national surveillance or causal evaluation.

Strengths and limitations. Strengths include broad global coverage, a longitudinal country-year design, country and year effects, country-clustered inference, explicit residual definitions, a cluster-robust specification test and a between-within decomposition targeted at the main data-construction concern.

The limitations are substantial. First, the ecological design cannot support individual-level or causal inference. Second, fixed effects do not eliminate time-varying confounding, reverse causality or country-specific trends. Third, the panel is unbalanced and complete-case selection may affect generalisability; some countries contributed few observations. Fourth, both outcomes are modelled international estimates, and the inactivity series uses obesity as a covariate; the between-within decomposition reduces but does not eliminate the resulting dependence. Fifth, internet use, services employment and dietary energy supply are broad proxies. Sixth, active-transport infrastructure, ultra-processed food sales, prices, digital-food-service use, policy implementation and within-country inequalities were unavailable as comparable annual global measures. Seventh, the GDP/year benchmark is intentionally simple and model-dependent; nonlinear GDP functions, region-specific trends or alternative development measures could change individual residuals and profile classifications. Future work should test alternative benchmark specifications and incorporate more direct measures of movement and food environments. Finally, country profiles have no uncertainty intervals and should not be interpreted as rankings.

CONCLUSIONS

In this ecological panel of 164 countries during 2000-2022, increases in insufficient physical activity were associated with increases in adult obesity within countries, and internet penetration remained positively associated with obesity after adjustment. Deviations above a common GDP/year benchmark for inactivity also co-varied with deviations above the obesity benchmark, including in the within- country component. The findings support integrated attention to movement, digital and food environments but do not establish causality. Movement Gap and Obesity Gap should be used only as transparent, model-dependent descriptive diagnostics.

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Ethics approval: Not applicable. The study used publicly available aggregate country-level data and did not involve human participants or identifiable records.

Data availability: The study used publicly available international datasets; source repositories are cited in the Methods and reference list.

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Address for correspondence:
Ekaterina Lyulina
Department of Martial Arts,
Uzbek State University of Physical Education and Sport,
Chirchik, Uzbekistan
email: sportuz8@gmail.com

Table 1. Descriptive statistics and definitions of indicators for the analytical sample, 2000-2022

Variable	N	Mean	SD	Min	Max
Adult obesity (%)	2,707	17.72	9.68	0.60	72.06
Insufficient physical activity (%)	2,707	26.61	10.85	2.70	66.14
ln GDP per capita, PPP	2,707	9.54	1.12	6.57	11.84
Internet users (%)	2,707	40.99	32.19	0.00	100.00
Dietary energy supply (kcal/capita/day)	2,707	2,897.33	476.53	1,401.07	3,966.57
Unemployment (%)	2,707	7.88	5.73	0.10	37.32
Urban population (%)	2,707	58.56	21.68	10.98	100.00
Population aged 65+ (%)	2,707	9.14	6.07	1.17	29.40
Secondary-school enrolment (%)	2,707	81.81	29.28	5.94	164.08
Employment in services (%)	2,707	55.27	17.60	8.58	89.73
Health expenditure (% GDP)	2,695	6.37	2.49	1.66	18.52

Indicator definitions*:* *Adult obesity* - percentage of adults aged 18+ years with BMI >=30 kg/m²; insufficient physical activity – percentage of adults aged 18+ years not meeting 150 min/week of moderate activity, 75 min/week of vigorous activity, or an equivalent combination; *GDP per capita, PPP* – GDP per capita based on purchasing-power parity, log-transformed; *internet users* – Individuals who used the Internet from any location during the previous 3 months (% of population); *dietary energy supply* – food supply available for human consumption (kcal/capita/day); *unemployment* – share of the labour force without work but available for and seeking employment (modelled ILO estimate); *urban population* – population living in urban areas (% of total population); *population aged 65+* – population aged 65 years and older (% of total population); *secondary-school enrolment* – gross secondary enrolment ratio, regardless of age; *employment in services* – employment in services (% of total employment; modelled ILO estimate); *health expenditure* – current health expenditure (% of GDP).

Note: Values refer to the complete-case sample used in the main model, except health expenditure. SD – standard deviation; PPP – purchasing power parity. Gross secondary-school enrolment may exceed 100% because total enrolment includes students outside the official age group.

Table 2. Two-way fixed-effects linear regression models predicting adult obesity prevalence (%)

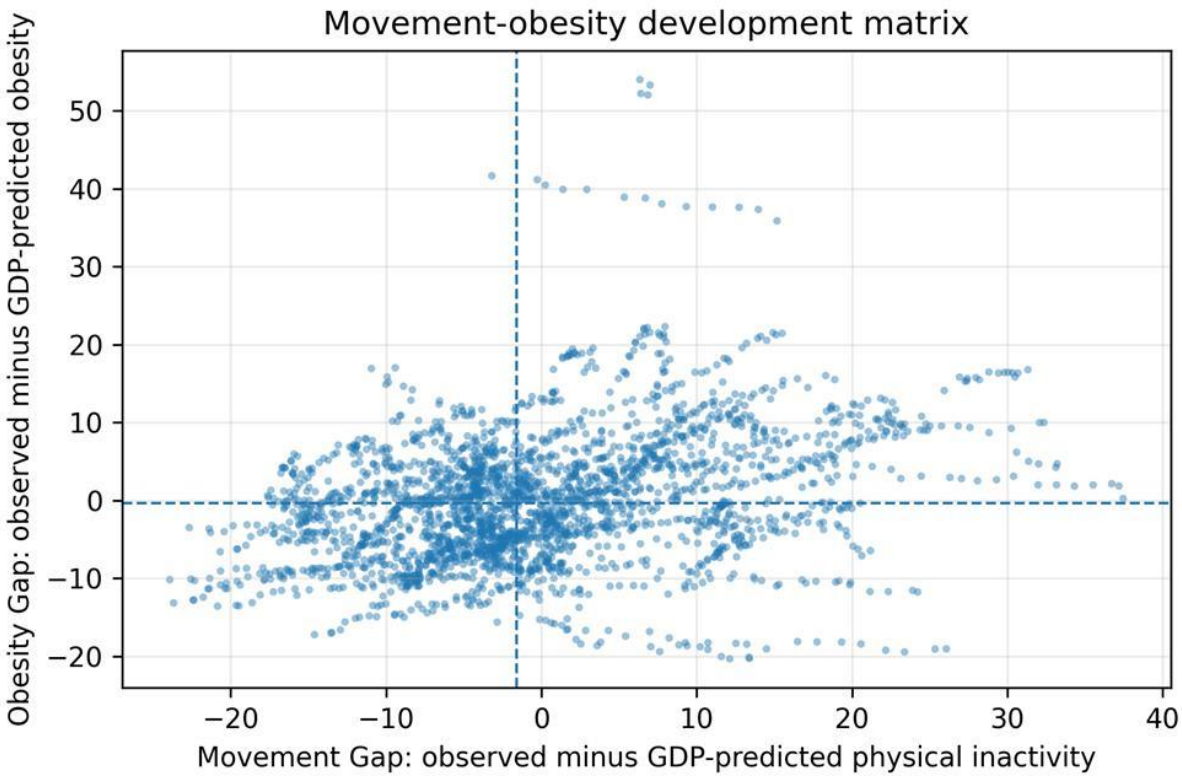
Predictor	**Model 1** No inactivity	**Model 2** Primary	**Model 3** + health exp.	**Model 4** Interaction
Insufficient physical activity (per +1 percentage point)	-	0.174*** (0.041)	0.175*** (0.042)	0.150** (0.049)
Internet users (per +1 percentage point)	0.054*** (0.009)	0.037*** (0.010)	0.037*** (0.010)	0.024 (0.020)
Internet × inactivity (per +1 unit of product term)	-	-	-	0.0004 (0.0005)
ln GDP per capita, PPP (per +1 log unit)	0.096 (1.041)	-0.967 (0.904)	-1.012 (0.911)	-0.768 (0.908)
Dietary energy supply (per +1 kcal/capita/day)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)
Unemployment (per +1 percentage point)	0.027 (0.032)	0.020 (0.030)	0.016 (0.030)	0.016 (0.029)
Urban population (per +1 percentage point)	-0.084* (0.037)	-0.081* (0.036)	-0.079* (0.036)	-0.080* (0.036)
Population aged 65+ (per +1 percentage point)	-0.322** (0.110)	-0.363** (0.116)	-0.364** (0.117)	-0.374** (0.117)
Secondary enrolment (per +1 percentage point)	0.013 (0.011)	0.014 (0.011)	0.014 (0.011)	0.014 (0.011)
Employment in services (per +1 percentage point)	-0.076* (0.037)	-0.056 (0.035)	-0.060 (0.036)	-0.053 (0.036)
Health expenditure (per +1 percentage point of GDP)	-	-	0.061 (0.076)	-
Observations	2,707	2,707	2,695	2,707
Countries	164	164	164	164
Within R^2	0.781	0.814	0.816	0.815

Note: The dependent variable is adult obesity prevalence (%). Coefficients are percentage-point changes in adult obesity associated with the unit change in each predictor stated in the first column, with country-clustered standard errors in parentheses. The interaction coefficient is per one-unit increase in the Internet users (%) × inactivity (%) product term. All models include country and year effects. $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$.

Table 3. Residual association, sensitivity analyses and between-within decomposition

Analysis	**Movement Gap coefficient (SE)**	**p**	**N**	**Countries**	**Within R^2**
Primary fixed-effects residual model	0.163 (0.045)	<0.001	2,707	164	0.341
+ health expenditure	0.164 (0.046)	<0.001	2,695	164	0.345
Countries with ≥5 observations	0.162 (0.045)	<0.001	2,661	150	0.342
Between-country component, unadjusted	0.285 (0.059)	<0.001	2,707	164	-
Within-country component, unadjusted	0.189 (0.047)	<0.001	2,707	164	-

Note: Obesity Gap is the dependent variable. Primary and sensitivity models include structural covariates, country effects, year effects and country-clustered standard errors. The unadjusted decomposition enters the country mean and year-specific deviation simultaneously.



Note: Dashed lines mark zero. Positive values are above the GDP/year prediction; negative values are below it. The plot is descriptive and does not represent causal effects or policy rankings.

Figure 1. Movement Gap and Obesity Gap across country-years