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Research Article

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Posted Date: November 16th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11120694/v1

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Additional Declarations: No competing interests reported.

Pandemic-era clustering of fitness deficits: an eight-year within-student study

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Abstract

Background Physical-fitness surveillance almost always reports one indicator at a time, so it cannot show whether different deficits occur together in the same person, or whether a major health shock changes that tendency. Chronic-disease epidemiology has shown that when conditions cluster within an individual, the clustering itself carries information beyond any single condition. We asked whether the COVID-19 pandemic increased the within-individual co-occurrence of fitness deficits in young adults, beyond any uniform decline in single indicators, and whether the change was concentrated in the cardiorespiratory system.

Methods We used eight academic years of mandatory fitness testing (2018-2025) from one Chinese university, comprising 276,406 records from 101,867 repeatedly tested students. We first confirmed, as background, that single indicators declined, comparing each student with their own baseline. We then tested whether four binary deficits (endurance, standing long jump, strength, vital capacity) co-occurred more than expected during the pandemic, using co-occurrence ratios, latent-variable models, a within-student comparison of the number of deficits, and a network permutation test. All estimates are associations, not causal effects.

Results Deficits became markedly more likely to co-occur within the same student during the pandemic. Because the co-occurrence ratio already accounts for how often each deficit occurs alone, its rise (men 1.27 to 1.40, women 1.53 to 2.09) indicates tighter clustering rather than more frequent failure. A cardiorespiratory deficit class in men rose from 6.2% (2021) to 9.3% (2023), and a threshold-free profile analysis reproduced the expansion, ruling out a scoring artifact. Against each student's own trajectory, the number of deficits rose 0.99 more during the pandemic than in a placebo window in men (95% CI 0.96 to 1.02) and 0.74 in women. The deficit network became denser (global strength 0.58 to 0.96, permutation P = 0.001). The change was cardiorespiratory-selective, with vital capacity and endurance worsening while jump and sprint did not.

Conclusions During the pandemic, fitness deficits became more likely to accumulate within the same young adult, a structural change concentrated in the cardiorespiratory system. Surveillance that follows individuals over time and monitors the number and combination of deficits against absolute health standards would detect this, whereas single-indicator monitoring against relative ranks would not.

Keywords COVID-19 · physical fitness · fitness-deficit co-occurrence · latent class analysis · network analysis · within-student comparison · cardiorespiratory endurance · university students

Background

The COVID-19 pandemic disrupted the daily lives of young people through school closures, social isolation, and prolonged sedentary confinement, reducing opportunities for physical activity for hundreds of millions of students. University students are in an important developmental window and depend heavily on campus facilities for exercise, so their cardiorespiratory fitness may have been affected through reduced activity, changes in diet, and the direct physiological effects of SARS-CoV-2 infection [1,2]. Lockdowns also changed eating behaviour [3] and increased anxiety, depression, and academic burnout [4], which can affect cardiorespiratory function through neuroendocrine and inflammatory pathways. Clinical work has shown that people with long COVID have impaired skeletal-muscle mitochondrial function and worse symptoms after exertion [5], and reduced oxygen uptake on exercise testing [6], and large cohorts have confirmed long-term cardiovascular effects [7,8]. These findings suggest that any effect of the pandemic on fitness should fall most heavily on the aerobic-endurance system.

Most existing evidence on pandemic-era fitness has a common limitation that motivates this study. Studies treat each fitness indicator on its own and report how often students fail each test. They therefore cannot say whether several deficits occur together in the same student more often than chance, whether that co-occurrence forms recognisable deficit combinations, or whether an acute shock changes the way deficits cluster. This matters because chronic-disease epidemiology has repeatedly shown that co-occurring conditions carry prognostic meaning that single conditions do not [9,10,11], and that the specific combinations are not random but reflect shared underlying pathways [12]. The framework built around this idea, which measures how conditions cluster within individuals using latent-variable and network methods, is well developed for chronic disease but has not been applied

to physical fitness. Standardised fitness testing still reports single-item pass or fail rates and does not ask whether deficits cluster within individuals into identifiable profiles, let alone whether a public-health shock can change that clustering.

This study asks one question. Did the pandemic increase the within-individual co-occurrence of fitness deficits, beyond any uniform decline in single indicators, and was the change concentrated in the cardiorespiratory system? We use eight years of fitness testing from one Chinese university, in which each student is tested repeatedly, so that deficits can be followed within the same person. Our hypothesis is that the pandemic did not only lower individual indicators but tightened the clustering of deficits within students, producing a shift from isolated deficits toward co-occurring cardiorespiratory deficits. Because COVID-19 was a global exposure with no unexposed comparison group, this is an observational study and its estimates are pandemic-era associations rather than causal effects.

Methods

Study design and population

We used the annual China National Student Physical Fitness Standard testing data of one comprehensive Chinese university for 2018–2025. Every undergraduate takes one standardised test each academic year. The eight years cover a pre-pandemic baseline (2018–2020), the pandemic-disruption period (2021–2022), and the post-pandemic period (2023–2025). Tests were conducted on campus each autumn by trained physical-education teachers using calibrated equipment under a uniform protocol. The raw database held 276,406 records. After removing special statuses and physiologically implausible values (vital capacity below 500 or above 8,000 mL, endurance time below 120 or above 600 s), the data were analysed. All records were anonymised before analysis. The study was approved by the Special Committee on Academic Ethics and Science and Technology Ethics, Guangdong University of Technology. The informed-consent documentation is described in the Ethics approval and consent to participate section. These are institutional administrative records and are not available as a public, citable dataset.

Fitness measures and deficit definitions

Five indicators were assessed under the national standard: vital capacity (mL), 50 m sprint (s), endurance run (men 1000 m, women 800 m, in s), standing long jump (cm), and a sex-specific strength test (pull-ups for men, one-minute sit-ups for women). The strength

indicator was extracted from each year's raw files and its cut-points checked against the official 2018 score columns, with 97–99% agreement.

For the co-occurrence analyses we defined four binary deficits (endurance, standing long jump, strength, vital capacity) using the national 60-point pass standard, an absolute, sex-specific health threshold. As sensitivity analyses we repeated the definition using within-cohort 25th and 33rd percentile ranks. The 50 m sprint was excluded from the co-occurrence analyses because more than 90% of students failed it in both sexes, which reflects a demanding standard and sedentary habits rather than a pandemic-specific change. This left four deficits.

Background: single-indicator change

To establish the background against which co-occurrence is interpreted, we estimated how single indicators changed during the pandemic using individual fixed-effects comparisons. Each student is compared with their own earlier tests, which removes all stable between-student differences. For an outcome Y of student i in year t,

$$Y_{it} = \alpha_i + \sum_{k \neq \text{ref}} \beta_k \cdot \mathbf{1}(\text{Year}_t = k) + \varepsilon_{it}$$

where α_i is the student fixed effect, β_k is the difference of year k from the reference year, and standard errors are clustered by student. The primary reference year was 2021, with 2019 reported as an alternative. Vital capacity was the primary continuous indicator and the endurance run the secondary one. We separated pandemic-era change from an ongoing developmental trend by extrapolating the 2018–2020 pre-pandemic slope forward and subtracting it. As a check, we also placed a synthetic "treatment" in 2019, within the pre-pandemic window, where no true effect should appear. We report these single-indicator results as background and interpret them cautiously, because without an unexposed comparison group this design cannot separate the pandemic from other changes that happened at the same time (the Limitations section). We also report a cohort-stratified version that compares each enrolment cohort with its own 2021 baseline; because all students were exposed at once, this is a before-and-after summary rather than a difference-in-differences, and we use it only to describe differences between cohorts.

Central question: co-occurrence of deficits

We tested whether the four deficits co-occurred more than expected, and whether this changed during the pandemic, in four complementary ways.

First, for each pair of deficits we computed an observed-to-expected co-occurrence ratio, defined as the observed joint failure rate divided by the product of the two individual failure rates. A ratio above one means the two deficits occur together more often than if they were independent. Because the ratio already accounts for how often each deficit occurs on its own, a rise in the ratio from before to during the pandemic indicates tighter clustering rather than a uniform increase in failure. We compared the pre-pandemic period (2018–2021) with the pandemic period (2022–2023) and attached bootstrap confidence intervals.

Second, we used latent class analysis on the four binary deficits to identify combinations of deficits that occur together, choosing the number of classes for each sex by the Bayesian information criterion together with interpretability and minimum class size [13,14]. To confirm that any change is not an artifact of the pass threshold, we repeated the analysis as a latent profile analysis on the four continuous z-scores, which uses the full distribution and no threshold, and tracked the prevalence of the resulting profiles by year.

Third, to test whether within-person accumulation of deficits was specific to the pandemic, we compared each student with their own pre-pandemic trajectory. Among students observed in three windows (pre-pandemic 2018–2019, placebo 2020–2021, and pandemic 2022–2023), we computed the change in the number of deficits during the pandemic minus the change during the earlier placebo window, with paired t-tests and 95% confidence intervals, and a table comparing included and excluded students.

Fourth, we represented the four deficits as a network in which edges are the pairwise correlations between deficits. Node strength is the sum of a node's absolute edge weights, and global strength is the sum of all absolute edge weights. Using a network comparison test [15], we relabelled pre-pandemic and pandemic observations at random 1,000 times to test whether the change in global strength was larger than expected by chance.

Follow-up analyses of the co-occurrence structure

Two follow-up analyses examined longitudinal associations between baseline deficits and subsequent fitness outcomes. Among students without a given cardiorespiratory deficit at baseline (2021), logistic regression estimated the association between each baseline deficit and the later appearance of that cardiorespiratory deficit during the pandemic. We also grouped students by their baseline deficit burden and compared the mean number of deficits after the pandemic (2024–2025). These analyses describe longitudinal associations and group differences; they do not evaluate incremental predictive performance beyond individual indicators.

Secondary analyses

We report a set of secondary analyses to characterise heterogeneity and to guard against alternative explanations: fixed-effects estimates stratified by BMI category and by sex; the relation between the number of pandemic-period tests and endurance change, reported both pooled and within enrolment cohort; clustering of individual recovery trajectories. Analyses used Python (linearmodels, statsmodels and scikit-learn) with two-sided $\alpha = 0.05$.

Results

Study population and the divergence of two systems

The database held 276,406 records from 101,867 students (men 191,341 records, 69.2%; women 85,065, 30.8%), with a median of three tests per student (Table 1). By the national standard, the most common deficit in men was strength (51.7%), followed by endurance (24.1%), jump (18.5%), and vital capacity (8.0%); in women it was endurance (15.5%), jump (11.4%), strength (6.8%), and vital capacity (2.8%) (Table 2). Cardiorespiratory and musculoskeletal indicators diverged from 2022: endurance and vital capacity worsened while standing long jump and the 50 m sprint stayed close to their pre-pandemic values (Figure 1). This divergence defines the two systems whose deficits we then study for co-occurrence.

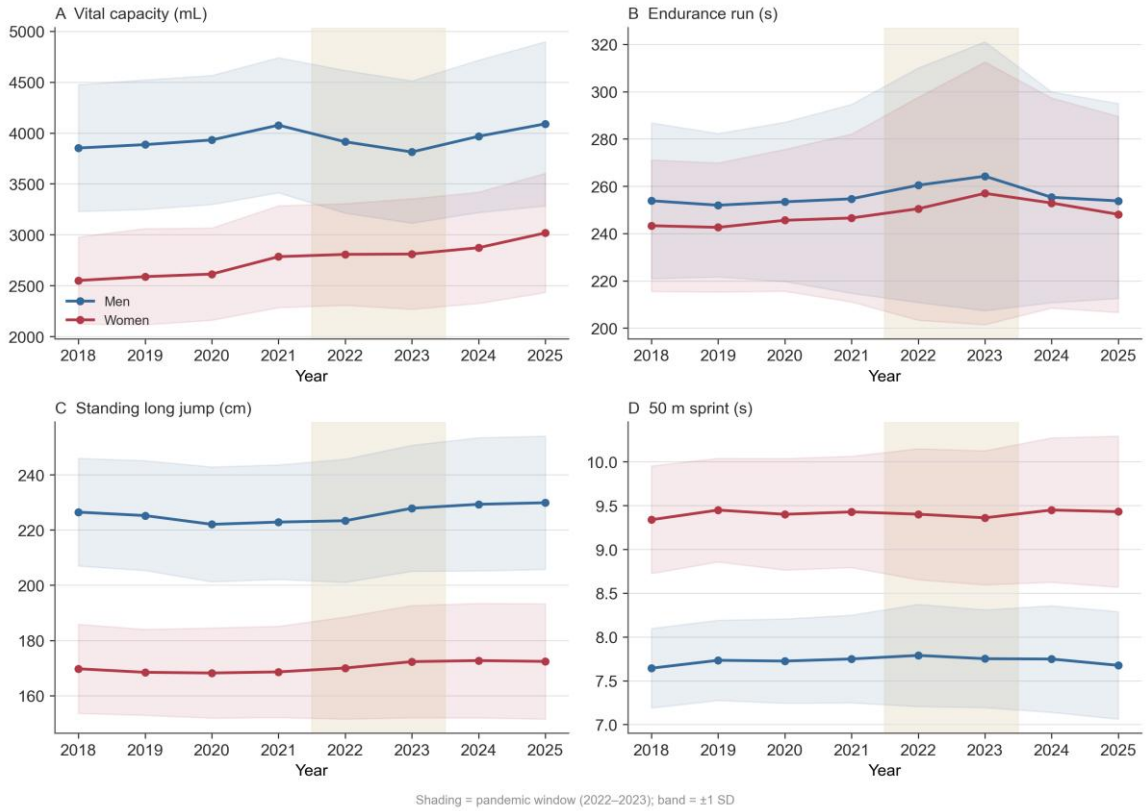


Figure 1. Annual trends of cardiorespiratory (endurance, vital capacity) and musculoskeletal (jump, 50 m sprint) indicators, 2018–2025.

Table 1. Characteristics of the study population (mean ± SD or n).

Characteristic	Total	Men	Women
Raw records (n)	276,406	191,341 (69.2%)	85,065 (30.8%)
Unique students (n)	101,867	70,970	30,897
Median tests per student	3	3	3
Height (cm)	168.3 ± 8.1	172.0 ± 6.1	159.9 ± 5.6
Weight (kg)	60.0 ± 11.5	63.8 ± 10.9	51.3 ± 7.5
BMI (kg/m²)	21.1 ± 3.2	21.5 ± 3.3	20.1 ± 2.6
Vital capacity (mL)	3,579 ± 846	3,939 ± 693	2,754 ± 526
Standing long jump (cm)	208.8 ± 33.0	225.7 ± 22.0	170.2 ± 18.3
50 m sprint (s)	8.2 ± 1.0	7.7 ± 0.5	9.4 ± 0.8

Table 2. National-standard failure rates and baseline BMI distribution.

Indicator or stratum	Men	Women
Failure, strength	51.7%	6.8%
Failure, endurance	24.1%	15.5%
Failure, long jump	18.5%	11.4%
Failure, vital capacity	8.0%	2.8%
Failure, 50 m sprint	>90%	>90%
BMI underweight (<18.5)	17.2%	28.9%
BMI normal (18.5–23.9)	66.0%	64.5%
BMI overweight or obese (≥24.0)	16.9%	6.6%

Background: single indicators declined, and only in the cardiorespiratory system

Single fitness indicators worsened during the pandemic, and the change was confined to the cardiorespiratory system. This establishes that real deficits appeared, and it is the background for the co-occurrence analyses that follow. Vital capacity, compared with each student's 2021 baseline, was 98.5 mL lower in 2022 and reached its lowest point 170.4 mL below baseline in 2023, then recovered to 50.7 mL below baseline in 2024 and returned to baseline by 2025. The endurance run changed in the same direction but more persistently, with men slower from 2022 (25.2 s in 2022, 50.8 s in 2023) and no recovery by the end of the study. After subtracting the pre-pandemic developmental trend, the pandemic-era shortfall in vital capacity remained substantial (311.7 mL in 2023). By contrast, standing long jump and the 50 m sprint showed no meaningful change (Table 3). The result did not depend on the reference year (Additional file 1: Fig. S1) and was reproduced by the cohort-stratified before-and-after summary (Additional file 1: Fig. S2).

We report these single-indicator estimates as background and interpret them cautiously. The pre-pandemic coefficients were not flat, and a placebo treatment placed in 2019 produced a significant coefficient in the improving direction (−6.06 s, $P < 0.001$), which shows an ongoing developmental trend of about 10–12 s per year in endurance. The 2022 change was several times larger than this trend and in the opposite direction to the placebo, so a pandemic-era break is still visible, but these estimates should be read as pandemic-era

associations, not causal effects (the Limitations section). Figure 2 summarises the pre-trend, the placebo test, and the cardiorespiratory-versus-musculoskeletal contrast.

Table 3. Change in each indicator during the pandemic (individual fixed effects, men, 2022–2023 vs baseline).

Indicator	System	Estimate	SE	P
Endurance (1000 m)	Cardiorespiratory	+3.82 s	0.24	<0.001
Vital capacity	Cardiorespiratory	−140.7 mL	3.2	<0.001
Standing long jump	Musculoskeletal	+0.07 cm	0.09	0.417
50 m sprint	Musculoskeletal	+0.007 s	0.003	0.012

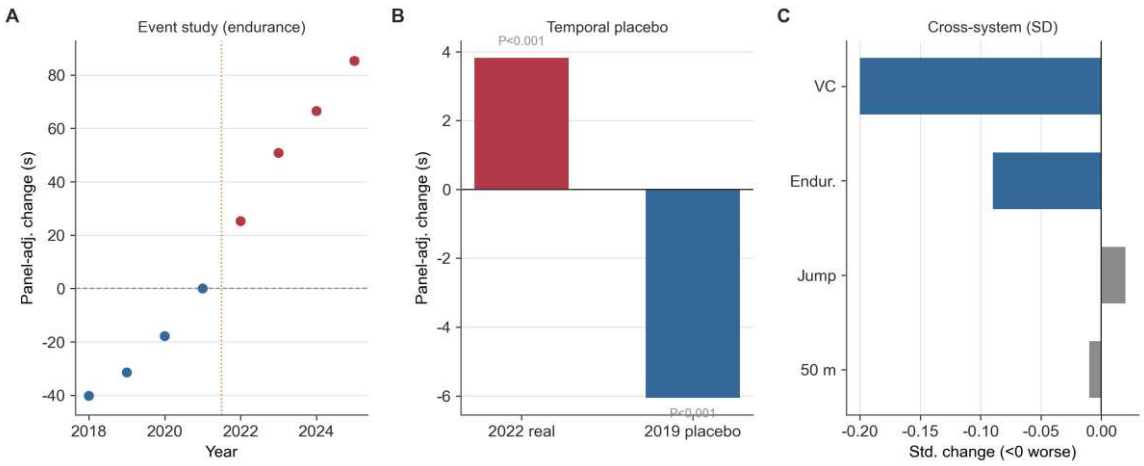


Figure 2. Diagnostics for the single-indicator background: event-study pre-trend (top), the 2019 placebo test (bottom-left), and the cardiorespiratory-versus-musculoskeletal contrast (bottom-right).

Deficits co-occurred more within the same student during the pandemic

Deficits clustered within students well above chance, and the clustering tightened during the pandemic. Every pair of deficits co-occurred more often than independence would predict (all observed-to-expected ratios above one; Table 4). More importantly, the average ratio rose from the pre-pandemic period to the pandemic period, from 1.27 to 1.40 in men and from 1.53 to 2.09 in women. Because this ratio already accounts for how often each deficit occurs on its own, its rise means the deficits clustered more tightly than expected from their individual failure rates, not simply that more students failed each test. In parallel, the proportion of students with two or more deficits rose from 2021 to 2023 in both sexes (men 24.7% to 31.7%, women 3.9% to 9.5%).

Table 4. Pairwise co-occurrence of deficits (observed-to-expected ratio) overall and from before to during the pandemic.

Deficit pair	Men, overall [95% CI]	Men, pre → pandemic	Women, overall [95% CI]	Women, pre → pandemic
Endurance + jump	1.66 [1.64, 1.68]	1.58 → 1.65	2.03 [1.98, 2.09]	1.66 → 1.93
Endurance + strength	1.35 [1.35, 1.36]	1.24 → 1.50	2.01 [1.93, 2.09]	1.61 → 2.54
Endurance + vital capacity	1.24 [1.21, 1.27]	1.05 → 1.27	1.38 [1.27, 1.48]	0.88 → 1.64
Jump + strength	1.43 [1.42, 1.44]	1.29 → 1.58	1.91 [1.82, 2.01]	1.91 → 2.05
Jump + vital capacity	1.34 [1.31, 1.38]	1.46 → 1.28	1.85 [1.71, 2.01]	1.76 → 2.12
Strength + vital capacity	1.00 [0.99, 1.02]	0.97 → 1.15	1.71 [1.52, 1.91]	1.37 → 2.25
Mean	1.34	1.27 → 1.40	1.82	1.53 → 2.09

The public-health reading of the sensitivity analysis is instructive. The rise in simultaneous endurance and vital-capacity deficits was clear under the absolute national standard (+3.0 percentage points) but much smaller under within-year percentile ranks (25th +1.1, 33rd +1.4 points). Part of the pandemic-era increase in failure was therefore a uniform downward shift that relative ranks hide, while the rise in the co-occurrence ratio shows that, on top of that shift, genuine clustering also increased. Surveillance during emergencies should use absolute health standards rather than within-cohort ranks, which can mask a general decline.

The co-occurring deficits form an identifiable, expanding profile

The deficits that clustered together formed a recognisable cardiorespiratory profile, and that profile expanded during the pandemic. Latent class analysis gave three classes in men and two in women (Table 5, Figure 3). In men these were a low-deficit class (50.1%), a musculoskeletal class with high strength and jump failure (34.1%), and a cardiorespiratory class (15.8%) with simultaneously raised endurance and vital-capacity failure. In women there was a low-deficit class (77.0%) and a multi-deficit class (23.0%). Because women's low failure rates make the binary classes less stable, we treated the continuous profile analysis as primary for them.

Table 5. Latent class profiles: conditional failure probability by class (national-standard threshold).

Class	Prevalence	Endurance	Jump	Strength	Vital capacity
Men, low-deficit	50.1%	0.08	0.04	0.36	0.03
Men, musculoskeletal	34.1%	0.48	0.39	0.90	0.10
Men, cardiorespiratory	15.8%	0.23	0.16	0.21	0.19
Women, low-deficit	77.0%	0.07	0.05	0.03	0.02
Women, multi-deficit	23.0%	0.44	0.30	0.19	0.06

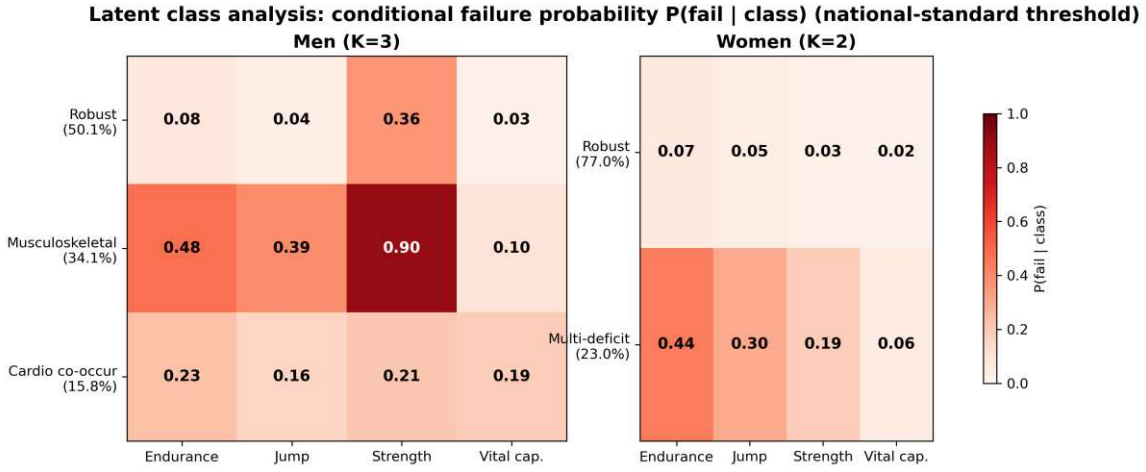


Figure 3. Latent class profiles: conditional failure probability P(fail | class) (men three classes, women two classes; national-standard threshold).

The continuous profile analysis confirmed that this expansion was not an artifact of the pass threshold. The number of profiles was chosen by the Bayesian information criterion (Additional file 1: Fig. S3). Using the full z-score distribution and no cut-point, it identified an endurance-dominant deficit profile in both sexes whose prevalence rose sharply during the pandemic, in men from 8.4% (2021) to 17.5% (2023) and in women from 8.1% to 18.1% (Figure 4). Tracking the latent classes by year gave the same result: the men's cardiorespiratory class rose from 6.2% (2021) to 9.3% (2023) and the women's multi-deficit class from 13.1% to 23.7%, matching the rise in the co-occurrence ratio in Table 4.

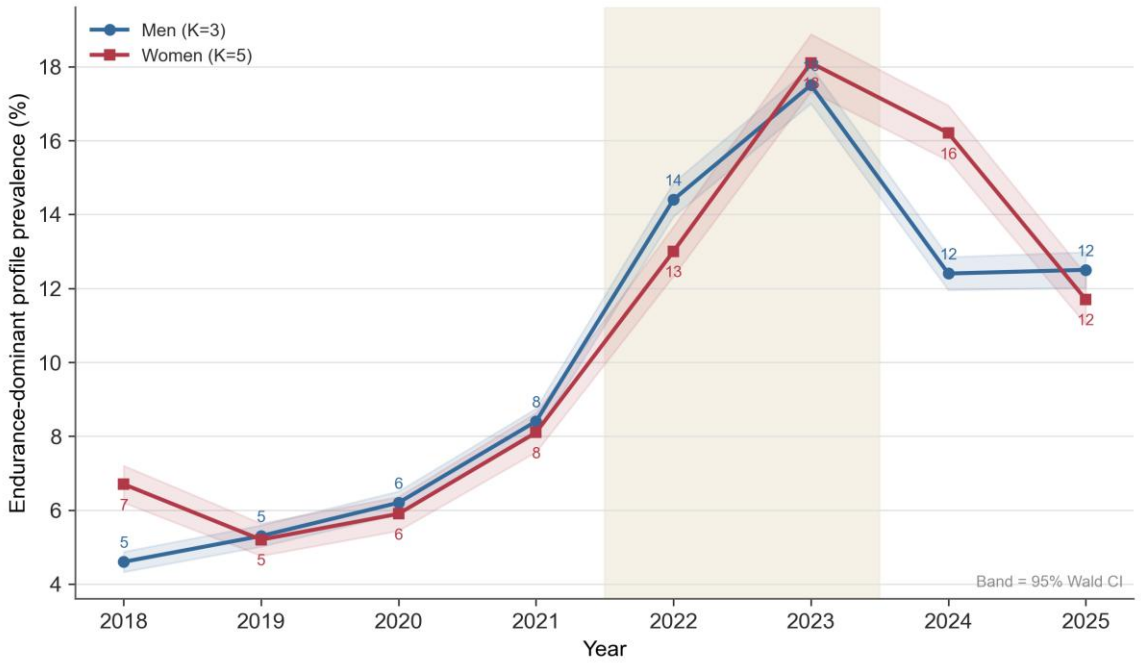


Figure 4. Yearly prevalence of the endurance-dominant deficit profile from the continuous latent profile analysis (threshold-free).

Within-student accumulation of deficits was specific to the pandemic

Comparing each student with their own earlier trajectory, the number of deficits rose during the pandemic well beyond what the same students showed in an earlier placebo window. Among students observed in all three windows, the number of deficits rose by 0.99 more during the pandemic than during the placebo window in men (95% CI 0.96 to 1.02, paired t = 55.9) and by 0.74 in women (Table 6). The share of students who worsened jumped from about 26% in the placebo window to about 72% during the pandemic (Figure 5). Because each student serves as their own comparison, this removes all stable between-student differences.

Table 6. Within-student change in the number of deficits (0–4), pandemic versus placebo window.

Group	N	Placebo change	Pandemic change	Pandemic − placebo [95% CI]	Paired t
Men	4,816	−0.08	+0.92	+0.99 [0.96, 1.03]	55.9
Women	2,118	−0.07	+0.67	+0.74 [0.70, 0.78]	34.3

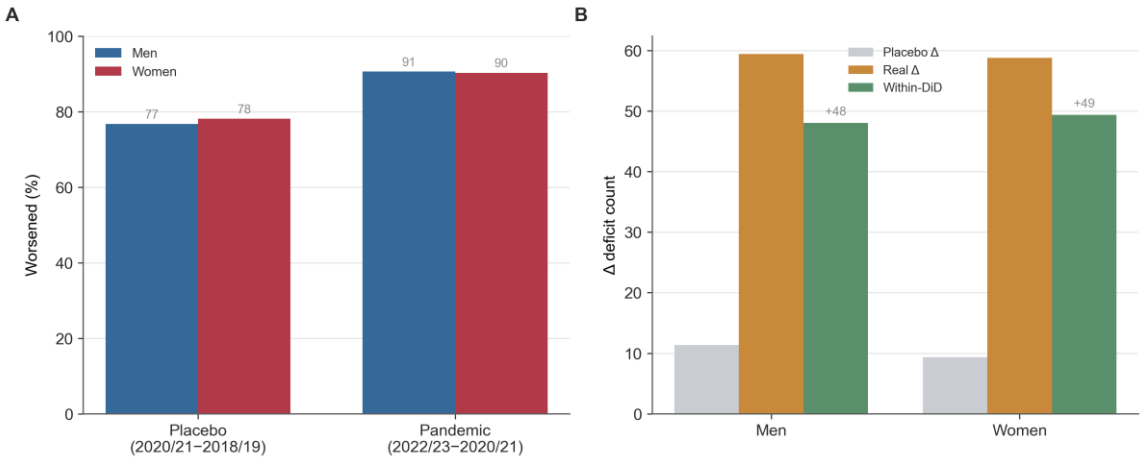


Figure 5. Within-student comparison: worsening rates across the three windows and the excess change during the pandemic.

Eligible students were concentrated in the 2019 enrolment cohort (men 4,741 of 4,816), whose cohort-specific estimate matched the pooled value. Included and excluded students differed mainly in enrolment year and slightly in baseline vital capacity, with other measures well balanced. Because the within-student comparison removes stable baseline differences, this does not bias the estimate, but it means the result mainly represents the 2019 cohort, and extension to other cohorts should be cautious.

The deficit network became denser during the pandemic

The correlations among deficits strengthened during the pandemic, giving direct network evidence of a change in the deficit structure, independent of the co-occurrence ratio and the latent-class models. Global connection strength rose from 0.58 to 0.96 (permutation P = 0.001). Every node became more central, with the largest gains for strength (0.38 to 0.62) and vital capacity (0.09 to 0.24), and every pairwise correlation strengthened, most for endurance with strength (+0.10) and strength with vital capacity (+0.08) (Figure 6).

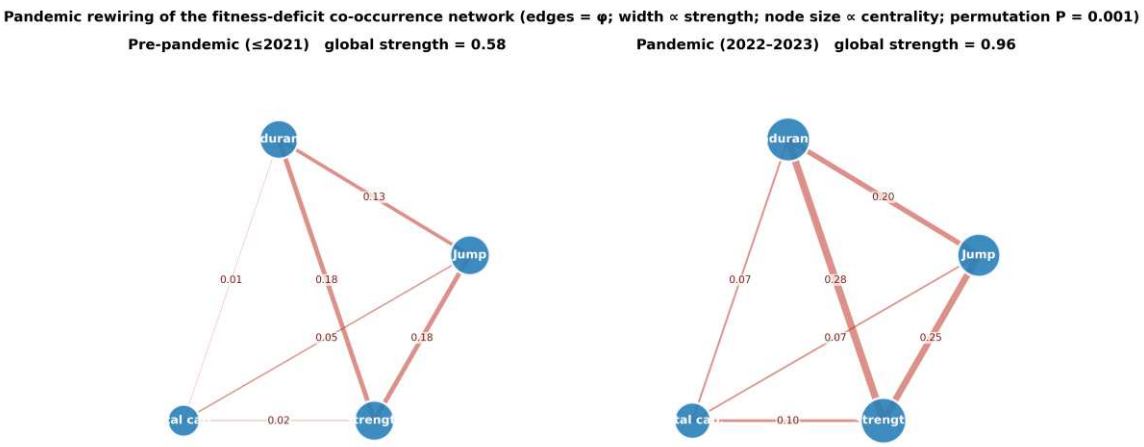


Figure 6. The fitness-deficit correlation network before and during the pandemic (edges are pairwise correlations; node size reflects centrality; permutation P = 0.001).

Baseline deficits were associated with subsequent fitness outcomes

Two further analyses examined longitudinal associations between baseline deficits and subsequent outcomes. First, among students who did not have a given cardiorespiratory deficit at baseline, a pre-existing musculoskeletal deficit was associated with acquiring that cardiorespiratory deficit during the pandemic. For a new vital-capacity deficit (N = 23,112, acquisition 9.9%), the adjusted odds ratios were 1.36 for a baseline strength deficit and 1.28 for a baseline jump deficit; for a new endurance deficit (N = 21,218, acquisition 45.4%), they were 1.32 for jump and 1.32 for vital capacity (Figure 7). These findings show that baseline musculoskeletal deficits were associated with subsequent cardiorespiratory deficits.

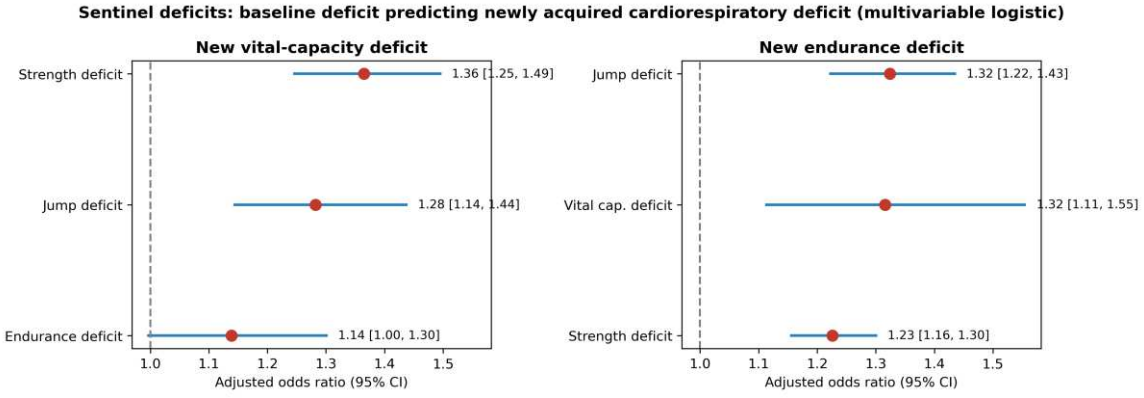


Figure 7. Association between each baseline deficit and the later appearance of a cardiorespiratory deficit during the pandemic (adjusted odds ratios, 95% CI).

Second, greater baseline deficit burden was associated with a higher mean number of deficits after the pandemic: 1.18 for students with no baseline deficit, 1.4 to 1.7 for one deficit, and 2.1 to 2.2 for two or more (Figure 8). Students with a single musculoskeletal

deficit had a higher subsequent mean deficit count than those with a single cardiorespiratory deficit (1.72 versus 1.44, P = 0.001). These group comparisons describe longitudinal differences; they do not establish incremental predictive value beyond individual fitness indicators.

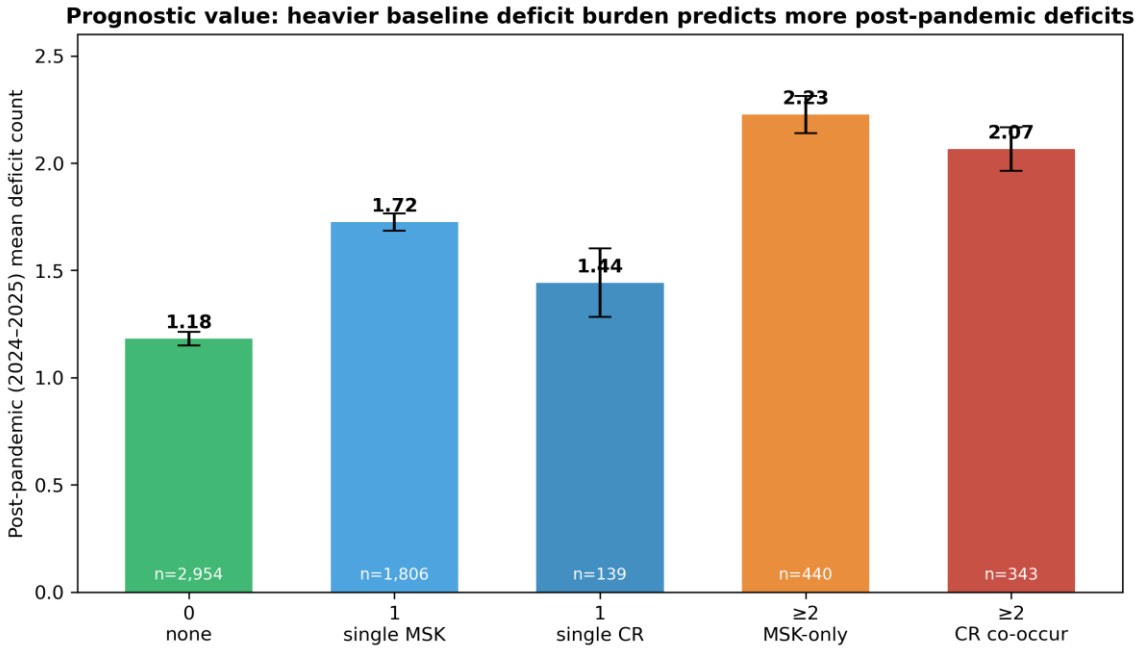


Figure 8. Mean number of deficits after the pandemic by baseline deficit burden.

Secondary analyses

The secondary analyses were consistent with the main findings and guard against alternative explanations. Endurance change during the pandemic followed a U-shaped gradient across BMI categories, worst in the overweight group and about 1.5 times the normal-weight value (Additional file 1: Fig. S4). The apparent sex difference (vital capacity lower in men, little change in women) is partly explained by women's ongoing baseline maturation in vital capacity (about 89 mL per year), which masks their pandemic-era shortfall, so the absence of change in women should not be read as absolute protection. The relation between the number of pandemic tests and endurance change reversed sign after accounting for enrolment cohort, from −13.19 to +2.47 s per test (Additional file 1: Fig. S5). This is a cohort-composition effect, not a cumulative-exposure effect, because students with more tests are simply tested at older ages. Trajectory clustering showed that more than half of affected students kept worsening from the shock into the recovery period (Additional file 1: Fig. S6), so the recovery seen in group means largely reflects cohort replacement rather than individual

recovery. Exploratory individual risk prediction showed limited performance and did not support screening use; complete methods and results are provided in Additional file 2.

Discussion

Main finding

Across eight years and 276,406 records, the pandemic did more than lower individual fitness indicators. It increased the tendency of distinct deficits to occur together within the same student. Four independent lines of evidence point the same way. The co-occurrence ratio, which is unaffected by how often each deficit occurs on its own, rose during the pandemic. Latent class and threshold-free profile models identified a cardiorespiratory deficit profile that expanded. Comparing each student with their own earlier trajectory, deficits accumulated during the pandemic far beyond a matched placebo window. The deficit network became denser on a permutation test. Because these methods rest on different assumptions and reach the same conclusion, the finding is robust to the weaknesses of any one of them. The change was concentrated in the cardiorespiratory system, consistent with the single-indicator background, in which endurance and vital capacity worsened while musculoskeletal indicators did not.

Interpretation and relation to previous work

Two features make this a structural change rather than a general decline. First, the co-occurrence ratio and the network are defined so that a uniform increase in failure would not move them. The fact that they moved means the deficits became more connected, not just more common. Second, the longitudinal analyses linked baseline musculoskeletal deficits with later cardiorespiratory deficits, and greater baseline deficit burden with a higher subsequent deficit count. These associations do not establish causal pathways or incremental predictive performance. A plausible biological reading is that a shared cardiorespiratory and metabolic pathway, stressed during the pandemic, pulls several fitness domains down together in susceptible students, so that deficits that were once independent begin to travel together. Clinical work on long COVID is consistent with such a shared pathway, including impaired muscle mitochondrial function and reduced oxygen uptake [5,6] and broad multi-organ involvement [16], although our administrative data contain no infection or behavioural records and cannot establish mechanism.

The single-indicator part of our results reproduces recent longitudinal studies. A four-year study of Chinese university students and a four-year cohort in Wuhan both found vital capacity peaking around 2021 and dropping in 2022, with the largest declines outside the obese group, matching our BMI pattern [17,18]. A European meta-analysis of more than 270,000 participants reported cardiorespiratory endurance still not recovered by 2023 [19], consistent with our finding that endurance had not recovered by 2025. These agreements are a strength, because they show our data behave like others'. The new contribution is the layer these studies did not examine: whether deficits co-occur within individuals and whether the pandemic changed that. To our knowledge this is the first application of the within-individual clustering and network framework from chronic-disease epidemiology to physical-fitness surveillance, and the first use of a network comparison test to show that a public-health shock strengthened the fitness-deficit network. The methods themselves are established; the contribution is the question they are used to answer and the finding they produce. Related work has used network analysis for children's fitness and mental health [20] and latent profiles for students' exercise experiences during the pandemic [21], but not the co-occurrence of fitness deficits or its change over an acute shock.

Implications for surveillance

The practical message is that single-indicator surveillance will miss what we found. Because part of the pandemic-era decline was a uniform downward shift, monitoring based on within-cohort ranks can show little change even as absolute fitness falls, so surveillance during emergencies should use absolute health standards. Because the informative signal is in the combination and number of deficits, surveillance should count deficits and track their combinations, not only report single-item pass rates. The associations between baseline and subsequent deficits support further evaluation of longitudinal monitoring that records both deficit counts and combinations. Their value for individual risk stratification remains to be established.

Limitations

Several limitations bound these conclusions. The sample is one university with a male majority (about 69%), so extension elsewhere needs care. There is no unexposed comparison group, and the pre-pandemic trend is not flat, so the single-indicator background cannot be read as the causal effect of the pandemic. Any change that coincided with the pandemic, such as facility closures or online physical education, could contribute. We therefore treat all

estimates as pandemic-era associations. The within-student comparison is the cleanest design here, but its placebo window (2020–2021) may itself be affected by early-pandemic disruption, which would make it conservative, and the eligible students are concentrated in the 2019 cohort. We lack individual infection status, home-exercise, diet, and mental-health data, so we cannot test mechanism. The women's latent classes are sensitive to the threshold and should be seen as sample-specific until replicated.

Conclusions

During the pandemic, fitness deficits in young adults did not only become more common one at a time. They became more likely to accumulate within the same person, a structural change concentrated in the cardiorespiratory system and shown consistently by co-occurrence ratios, latent-variable models, a within-student comparison, and a network test. Surveillance that follows individuals over time and monitors the number and combination of deficits against absolute health standards would detect this, where single-indicator monitoring against relative ranks would not. Further studies are needed to assess the mechanisms underlying these longitudinal associations and their generalisability to other populations.

Abbreviations

BMI: body mass index; CI: confidence interval; COVID-19: coronavirus disease 2019; FE: fixed effects; LCA: latent class analysis; LPA: latent profile analysis; OR: odds ratio; SARS-CoV-2: severe acute respiratory syndrome coronavirus 2; SD: standard deviation; SE: standard error.

Declarations

Ethics approval and consent to participate The study was approved by the Special Committee on Academic Ethics and Science and Technology Ethics, Guangdong University of Technology. This retrospective study used existing records from routine university student physical fitness testing conducted from 2018 to 2025. The data were not collected specifically for this research and were irreversibly anonymized, with all personal identifiers removed before analysis. The study involved no intervention, randomization, or additional testing of participants. The requirement for informed consent to participate was waived by the Special Committee on Academic Ethics and Science and Technology Ethics, Guangdong University

of Technology. All study procedures, including the use and analysis of human data, were conducted in accordance with relevant guidelines and regulations.

Consent for publication Not applicable.

Availability of data and materials The de-identified panel dataset and the analysis code are available from the corresponding author on reasonable request, under a data-use agreement with the participating university. The raw test data cannot be made publicly available because of the university's data-protection requirements.

Competing interests The authors declare that they have no competing interests.

Funding The authors received no specific funding for this work.

Authors' contributions HX and XW conceived and designed the study, jointly organised and cleaned the data, performed the statistical analyses, and interpreted the results. HX led the drafting of the manuscript, and XW contributed to its critical revision. Both authors reviewed and approved the final manuscript.

Acknowledgements Not applicable.

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Additional files

Additional file 1 (Supplementary figures and methods).

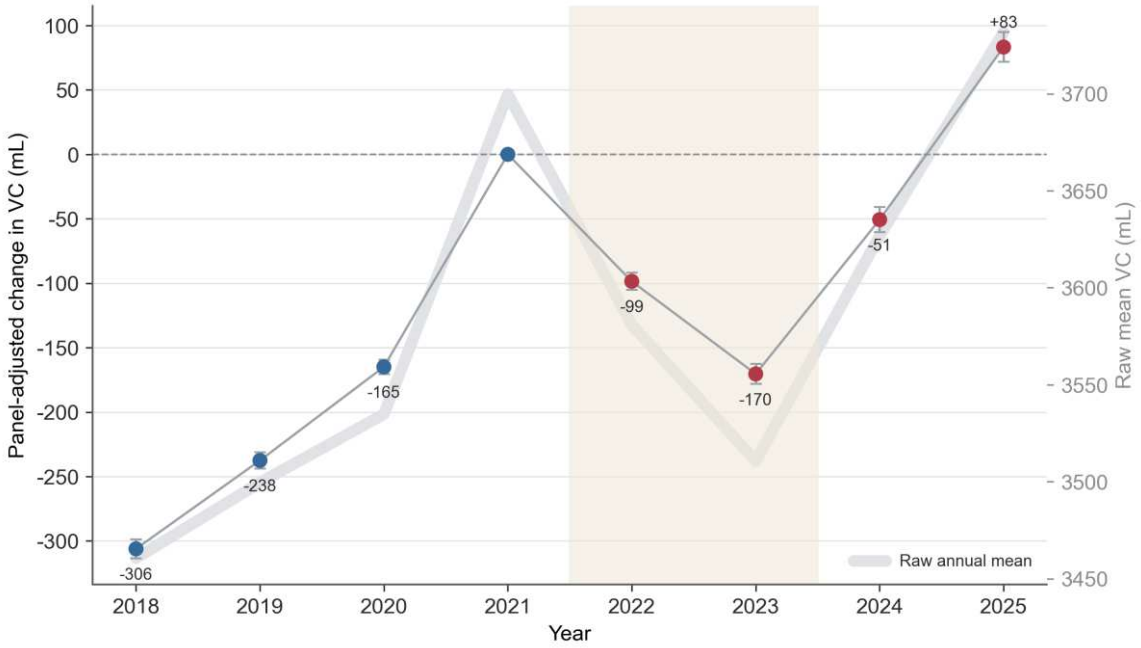


Fig. S1. Vital-capacity event study: trough in 2023 and recovery by 2025 (reference 2021; 95% CI).

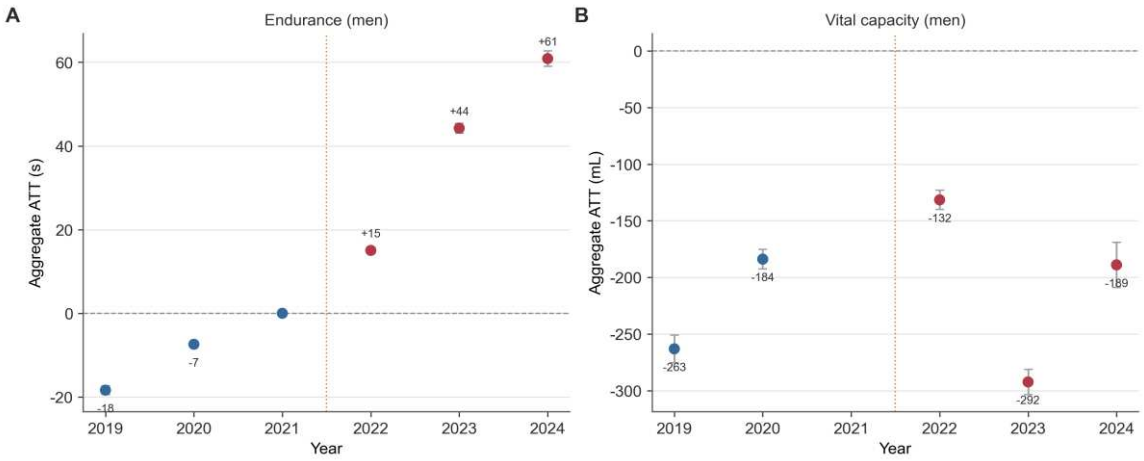


Fig. S2. Cohort-stratified before-and-after summary (left: endurance; right: vital capacity; 2021 baseline).

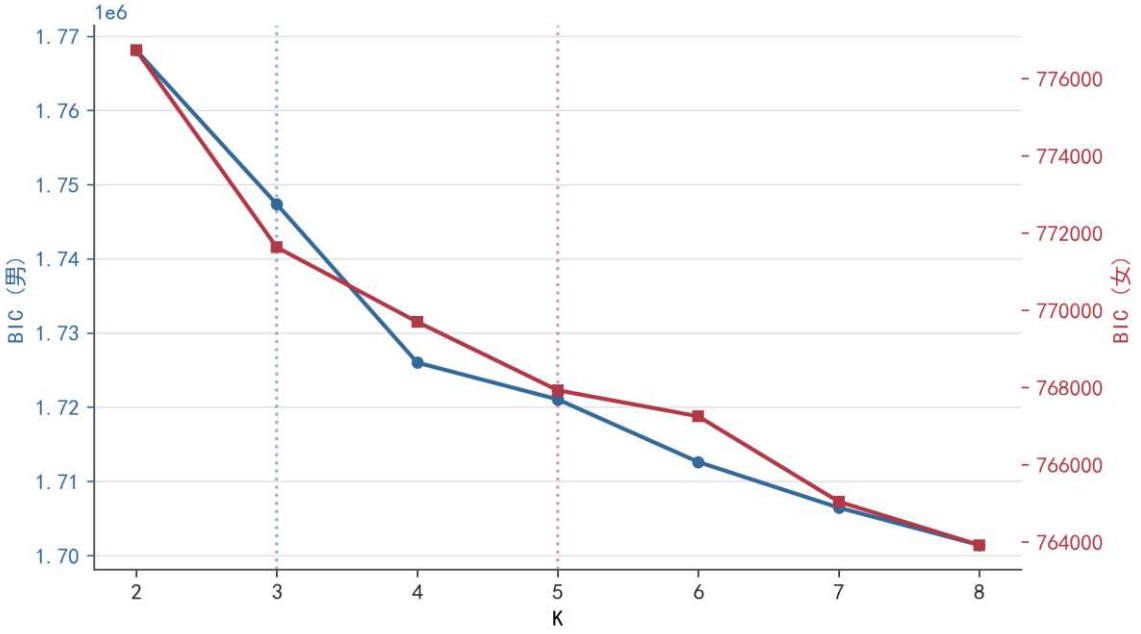


Fig. S3. Latent profile model selection: information criterion versus number of classes.

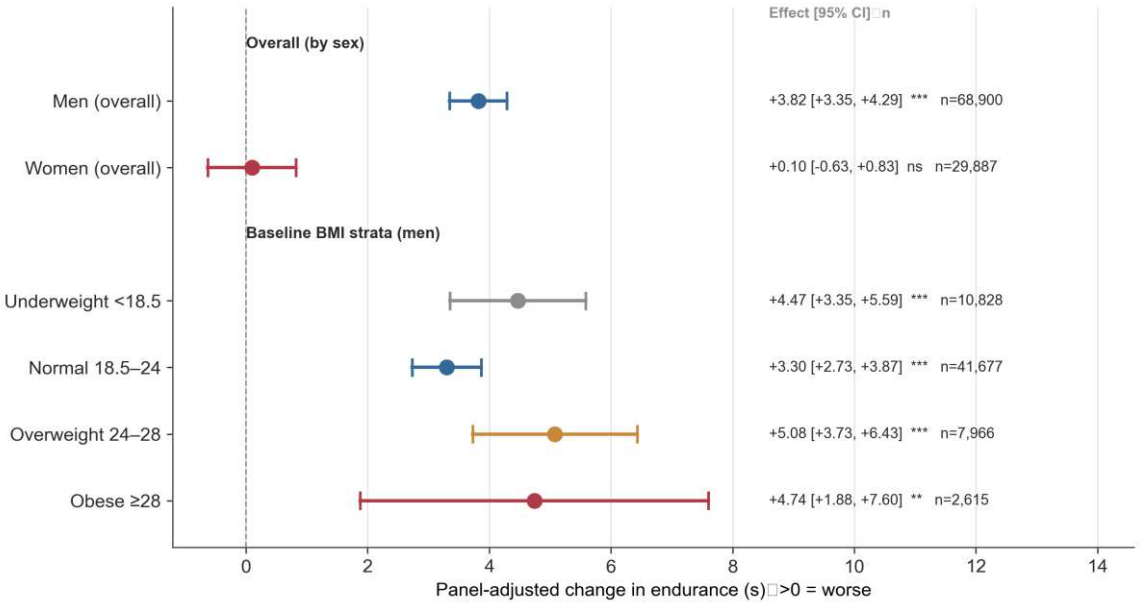


Fig. S4. Endurance change by BMI category (men; 95% CI).

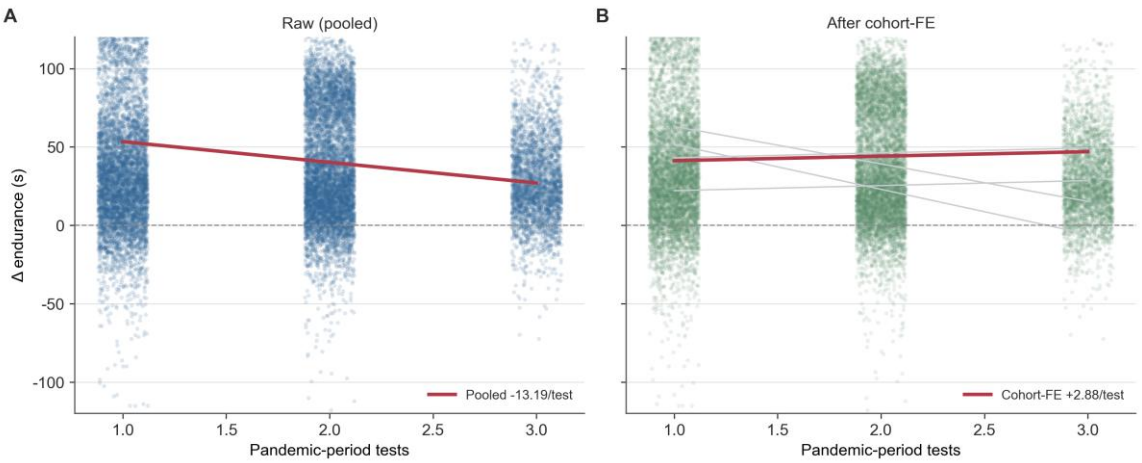


Fig. S5. Number of pandemic tests versus endurance change: pooled slope and the reversal after accounting for enrolment cohort.

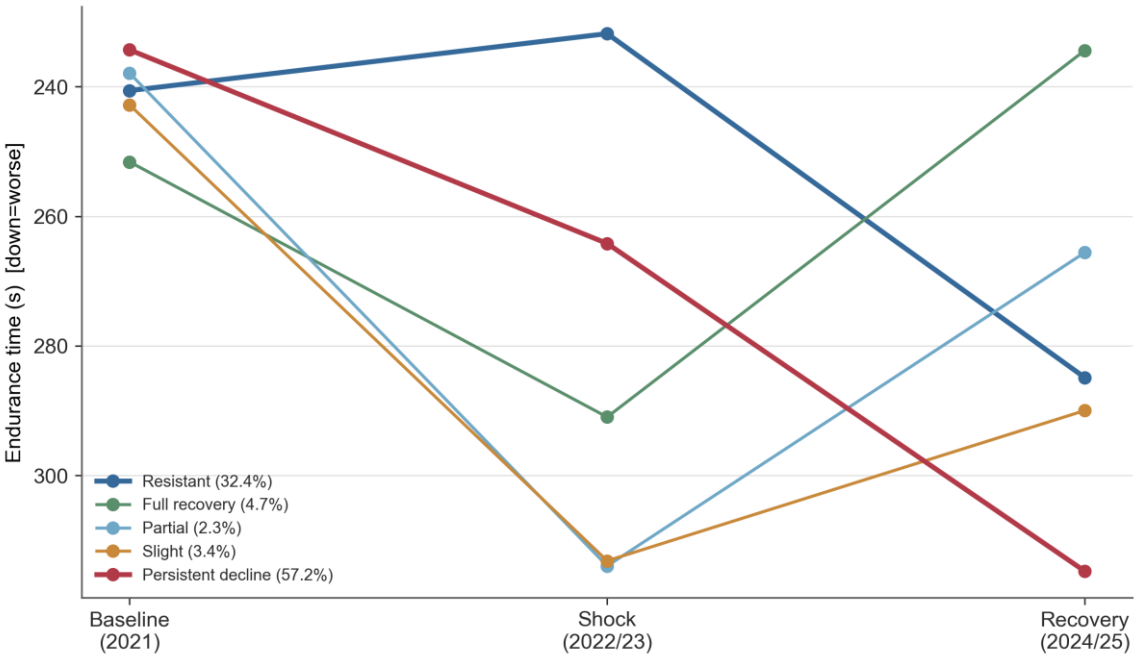


Fig. S6. Clustering of individual recovery trajectories (endurance, men).

Additional file 2. Exploratory prediction validation: methods, cohort accounting, performance and calibration (Tables S1–S3; Fig. S7). Supplied as a separate supplementary document.