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Vital Surveillances

Factors in Health Examination Rate Among Chinese Older Adults — China, 2013–2023

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ABSTRACT

Introduction: Health examinations are important components of primary prevention in older adults. This study aimed to assess temporal trends in health examinations in China and analyze the factors with their use.

Methods: To this end, four rounds of nationally and provincially representative cross-sectional surveys were conducted. Overall, 180,455 adults aged ≥ 65 years were included in this study. Weighted health examination rates were calculated for the overall population and the subgroups. The Anderson model analysis framework was used to analyze the associated factors.

Results: From 2013 to 2023, the health examination rate among older adults aged ≥ 65 years within 1 year increased from 21.8% to 66.6%, corresponding to an annual increase of 5.6% and an average annual percentage change of 6.49%. Disparities across the subgroups diminished rapidly, particularly in terms of residence, location, education, and income. Examinations provided free of charge by the community accounted for the vast majority of the subgroups. Need- and health-related behavioral factors were the primary determinants.

Conclusion: Over the past decade, substantial progress has been made in health examination rates for older adults, particularly among socially and economically disadvantaged populations. Further sustained policy and financial support should be implemented to achieve the universal coverage target for health examinations among older adults aged ≥ 65 years as defined by the Healthy China Initiative (2019–2030).

Health examinations, or health check-ups, are medical service activities and processes involving the

medical assessment and evaluation of the health status of individuals or populations. With the goal of initiating early interventions to prevent future illnesses, these examinations primarily focus on the screening of noncommunicable diseases and their risk factors, risk stratification and assessment, and the provision of health guidance and intervention recommendations (1). Health examinations are associated with greater opportunities for the detection and treatment of chronic diseases, improved risk factor control, increased uptake of preventive services, and better patient-reported outcomes (2). According to the National Bureau of Statistics of China, older adults aged ≥ 65 years accounted for 15.6% (220 million) of the population in 2024. The Healthy China Initiative (2019–2030) emphasizes improving health literacy among older adults, promoting participation in regular health examinations, and providing free annual health examinations for adults aged ≥ 65 years (3). Although our previous studies estimated health examination rates among Chinese adults aged ≥ 18 years from 2010 to 2018, evidence on current rates and trends in older adults remains limited (4). This study used four rounds of cross-sectional surveys to estimate the health examination rate among adults aged ≥ 65 years on the Chinese mainland and analyze the associated factors.

METHODS

Data were obtained from the China Chronic Disease and Risk Factor Surveillance (CCDRFS). To date, seven rounds of the survey have been conducted, in 2004, 2007, 2010, 2013, 2015, 2018, and 2023; each round adopted a similar multistage, stratified, clustered probability sampling design to generate a nationally and provincially representative sample. The details of the sampling schemes and sample weights of the CCDRFS have been described previously (5). Data from four surveys (2013, 2015, 2018, and 2023) were used.

Questionnaires were administered by trained and qualified health professionals to obtain information on socioeconomic status, lifestyle behaviors, history of major chronic diseases, and health examinations. Information regarding health examinations, excluding those conducted during medical consultations, included the date of the most recent examination. The reasons for undergoing an examination were also recorded.

Individuals with missing sample weights, information on health examinations, or associated factors were excluded. Individuals with inconsistent data (e.g., an examination date later than the survey date or a reported reason for the examination despite never having undergone one) were also excluded from the study. After stratification, clustering, and incorporation of sample weights, the weighted rate of health examinations was calculated by sex, age group, residence, location, education, ethnicity, and annual per capita income. Taylor series linearization with a complex sampling design and finite population correction was used to estimate 95% confidence intervals (CIs). Differences between subgroups and reasons for examination across subgroups were tested using the Rao-Scott chi-squared test. Joinpoint statistical software (version 5.4.0.0; Applications Branch, National Cancer Institute, Bethesda, MD, USA) was used to calculate the average annual percentage change (AAPC). Based on the Anderson model analysis framework, a weighted multivariate logistic regression model was used to identify the factors associated with health examination within 1 year. The associated factors were classified into four categories: predisposing, enabling, need, and health-related behavioral factors (6).

All data cleaning and analyses were performed using R software (version 4.4.2, R Foundation for Statistical Computing, Vienna, Austria). All tests were two-sided, and $P \leq 0.05$ was considered statistically significant.

RESULTS

This study included 180,455 older adults aged ≥ 65 years (29,870 in 2013, 35,861 in 2015, 46,713 in 2018, and 68,011 in 2023). The distributions of the subgroups were similar across all surveys (Table 1).

The weighted health examination rate is presented in Table 2. Between 2013 and 2023, the health examination rate steadily increased across all subgroups. The health examination rate within 1 year increased from 21.8% (95% CI: 18.9%–24.8%) in

2013 to 66.6% (95% CI: 64.4%–68.8%) in 2023, by 5.6% (95% CI: 5.1%–6.1%) annually (AAPC 6.49%). The rate rose similarly in men and women, by about 5.6% annually. The rates across different age groups were similar in 2013 ($P=0.336$), whereas that among those aged 75–79 years was higher in 2023. Individuals living in rural areas had a lower examination rate over the survey period (all P for difference <0.05). However, this disparity was rapidly diminishing (from 17.3% vs. 27.3% in 2013 to 65.0% vs. 68.6% in 2023). The examination rate increased faster among rural individuals, as reflected by the annual change (5.9% vs. 5.2%) and the AAPC (7.61% vs. 5.10%). Examination rates in different locations followed a similar trend; individuals in central and western areas exhibited a steeper increase. Significant increases were also observed in older adults receiving less education (from 19.3% in 2013 to 66.1% in 2023) and in those with the lowest annual per capita income (from 16.8% in 2013 to 64.9% in 2023).

In 2013, the reasons for undergoing health examinations, in descending order, were community-provided free examination (71.0%), self-care (14.4%), workplace-provided free examination (10.8%), and other reasons (3.8%) (P for difference <0.001). The proportion of community-provided examinations increased over time, reaching 73.6% in 2015, 81.3% in 2018 and 87.5% in 2023 (Figure 1). In 2023, the proportions of reasons differed significantly across subgroups. Examinations provided free by the community accounted for the vast majority across all subgroups, and the proportion was higher among those living in rural and central areas, and those aged 75–79 years. Notably, with increasing educational level and annual per capita income (except for those unwilling to disclose), the proportion of community-provided examinations decreased, while the proportion of self-care increased. Residence-specific reasons are presented in Supplementary Figure S1 (available at <https://weekly.chinacdc.cn/>).

Individuals who had never undergone a health examination were more likely to be younger, living in rural and western areas, and receiving less education (Supplementary Table S1, available at <https://weekly.chinacdc.cn/>). In the multivariable logistic regression models, older adults aged 70–74 years [odds ratio (OR)=1.11, 95% CI: 1.03–1.20] and 75–79 years (OR=1.20, 95% CI: 1.09–1.31) had higher odds of undergoing a health examination within 1 year than their younger counterparts. Compared with those without medical insurance, individuals with urban and

TABLE 1. General characteristics of individuals aged ≥ 65 years in China, 2013–2023 [No. (%)].

Characteristics	2013 (n=29,870)	2015 (n=35,861)	2018 (n=46,713)	2023 (n=68,011)
Sex				
Man	13,643 (45.7)	18,277 (51.0)	22,614 (48.4)	32,218 (47.4)
Woman	16,227 (54.3)	17,584 (49.0)	24,099 (51.6)	35,793 (52.6)
Age group, years				
65–69	12,997 (43.5)	16,827 (46.9)	22,576 (48.3)	29,182 (42.9)
70–74	8,320 (27.9)	9,967 (27.8)	13,430 (28.8)	22,337 (32.8)
75–79	5,379 (18.0)	5,691 (15.9)	6,791 (14.5)	10,936 (16.1)
≥ 80	3,174 (10.6)	3,376 (9.4)	3,916 (8.4)	5,556 (8.2)
Residence				
Urban	14,363 (48.1)	15,226 (42.5)	19,339 (41.4)	30,903 (45.4)
Rural	15,507 (51.9)	20,635 (57.5)	27,374 (58.6)	37,108 (54.6)
Location				
East	12,750 (42.7)	15,468 (43.1)	21,026 (45.0)	31,149 (45.8)
Central	7,254 (24.3)	8,776 (24.5)	11,208 (24.0)	16,262 (23.9)
West	9,866 (33.0)	11,617 (32.4)	14,479 (31.0)	20,600 (30.3)
Education				
Primary school or lower	22,080 (73.9)	26,328 (73.4)	33,792 (72.3)	45,775 (67.3)
Secondary school	4,672 (15.6)	5,964 (16.6)	8,725 (18.7)	14,177 (20.8)
High school	2,164 (7.2)	2,425 (6.8)	2,998 (6.4)	6,431 (9.5)
College or above	954 (3.2)	1,144 (3.2)	1,198 (2.6)	1,628 (2.4)
Ethnicity				
Han	27,354 (91.6)	32,788 (91.4)	42,710 (91.4)	62,461 (91.8)
Other	2,516 (8.4)	3,073 (8.6)	4,003 (8.6)	5,550 (8.2)
Annual per capita income, CNY				
<6,000	6,385 (21.4)	10,003 (27.9)	10,837 (23.2)	14,099 (20.7)
6,000–11,999	4,391 (14.7)	5,871 (16.4)	7,168 (15.3)	10,070 (14.8)
12,000–23,999	5,306 (17.8)	6,868 (19.2)	8,024 (17.2)	10,538 (15.5)
$\geq 24,000$	4,707 (15.8)	6,321 (17.6)	9,187 (19.7)	13,325 (19.6)
Refused/ do not know	9,081 (30.4)	6,798 (19.0)	11,497 (24.6)	19,979 (29.4)

Abbreviation: CNY=Chinese Yuan.

rural resident basic medical insurance were more likely to undergo health examinations ($OR=1.47$, 95% CI : 1.19–1.82). Additionally, the odds of undergoing health examinations were higher among individuals with 1 ($OR=1.56$, 95% CI : 1.44–1.69) or ≥ 2 ($OR=1.95$, 95% CI : 1.78–2.13) chronic diseases, former smokers and alcohol drinkers, but lower among current smokers, and physically inactive older adults (Figure 2).

DISCUSSION

In this study, four rounds of a large, cross-sectional, nationally representative survey — including 180,455

older adults aged ≥ 65 years — were utilized to estimate the health examination rate, the reasons for examination, and the associated factors. The examination rate within 1 year more than tripled over the past decade, rising from 21.8% in 2013 to 66.6% in 2023, particularly among individuals in rural areas, central and western regions, and those with lower education level or income. Examinations provided free of charge by the community accounted for most responses.

Health examinations have long been a common element of healthcare in some high-income countries (e.g., the United States and the United Kingdom) (7), whereas such initiatives were implemented relatively

TABLE 2. Weighted health examination rate among individuals aged ≥ 65 years in China, 2013–2023. [% (95% CI)]

Characteristics	2013	2015	2018	2023	Annual change*	AAPC (%)
Examination within 5 years	31.0 (27.6–34.5)	55.7 (52.5–58.9)	63.9 (61.5–66.4)	77.1 (75.1–79.1)	5.8 (5.3–6.3)	5.23
Examination within 3 years	30.3 (27.0–33.7)	54.8 (51.6–58.0)	63.1 (60.6–65.5)	76.3 (74.3–78.4)	5.8 (5.3–6.2)	5.33
Examination within 1 year [†]	21.8 (18.9–24.8)	44.5 (41.5–47.5)	52.7 (50.1–55.2)	66.6 (64.4–68.8)	5.6 (5.1–6.1)	6.49
Sex						
Man	20.9 (18.1–23.8)	44.0 (41.4–46.7)	52.5 (49.9–55.1)	65.8 (63.5–68.2)	5.6 (5.2–6.1)	6.46
Woman	22.6 (19.4–25.8)	44.9 (41.4–48.4)	52.8 (50.2–55.5)	67.3 (65.1–69.5)	5.6 (5.1–6.1)	6.59
<i>P</i> for difference	0.019	0.400	0.667	0.017		
Age group, years						
65–69	21.5 (18.5–24.5)	44.5 (41.9–47.1)	51.7 (49.2–54.1)	64.8 (62.6–67.1)	5.4 (4.9–5.9)	6.01
70–74	23.5 (20.3–26.7)	45.2 (42.3–48.1)	55.0 (52.0–58.0)	67.6 (65.0–70.2)	5.5 (5.0–6.0)	6.30
75–79	21.2 (17.6–24.7)	46.5 (42.4–50.7)	53.6 (50.4–56.8)	69.2 (66.5–71.9)	6.0 (5.4–6.6)	6.83
≥ 80	20.5 (15.4–25.5)	39.8 (33.9–45.8)	49.0 (45.7–52.2)	63.7 (60.8–66.6)	5.4 (4.7–6.1)	6.87
<i>P</i> for difference	0.336	0.045	<0.001	<0.001		
Residence						
Urban	27.3 (23.5–31.0)	51.1 (47.7–54.4)	56.3 (53.3–59.2)	68.6 (66.1–71.1)	5.2 (4.6–5.7)	5.10
Rural	17.7 (14.2–21.3)	39.3 (35.6–43.0)	49.9 (46.4–53.4)	65.0 (62.2–67.8)	5.9 (5.3–6.5)	7.61
<i>P</i> for difference	<0.001	<0.001	0.002	0.024		
Location						
East	28.5 (23.4–33.5)	49.0 (44.5–53.5)	56.1 (51.5–60.6)	68.8 (65.7–71.8)	5.0 (4.3–5.8)	5.51
Central	19.1 (14.9–23.4)	44.8 (39.1–50.6)	49.8 (46.1–53.5)	67.4 (62.8–72.1)	6.0 (5.3–6.8)	7.66
West	13.3 (9.0–17.5)	36.4 (32.6–40.3)	49.8 (46.0–53.6)	62.1 (58.0–66.3)	6.1 (5.4–6.8)	7.40
<i>P</i> for difference	<0.001	0.001	0.035	0.050		
Education						
Primary school or lower	19.3 (16.4–22.1)	41.7 (38.4–45.0)	51.1 (48.3–53.9)	66.1 (63.6–68.7)	5.8 (5.4–6.3)	7.44
Secondary school	26.9 (22.8–31.0)	48.6 (45.3–51.9)	55.6 (52.5–58.7)	67.0 (64.5–69.5)	5.0 (4.4–5.6)	5.11
High school	33.2 (27.6–38.8)	56.4 (52.7–60.1)	56.7 (53.1–60.3)	68.3 (65.8–70.8)	4.4 (3.6–5.2)	3.52
College or above	42.6 (33.6–51.5)	66.1 (60.6–71.6)	66.0 (61.0–71.0)	70.0 (66.4–73.5)	3.4 (2.2–4.6)	1.56
<i>P</i> for difference	<0.001	<0.001	<0.001	0.158		
Ethnicity						
Han	22.7 (19.7–25.7)	45.3 (42.2–48.4)	53.4 (50.7–56.2)	67.6 (65.3–69.9)	5.6 (5.1–6.1)	6.53
Other	11.5 (5.2–17.7)	33.4 (29.3–37.5)	43.7 (39.2–48.3)	53.9 (46.6–61.3)	5.3 (4.1–6.5)	6.95
<i>P</i> for difference	0.008	<0.001	<0.001	<0.001		
Annual per capita income, CNY						
<6,000	16.8 (13.8–19.8)	42.6 (38.6–46.7)	51.1 (48.2–53.9)	64.9 (61.9–67.9)	6.0 (5.5–6.5)	7.20
6,000–11,999	20.6 (16.9–24.2)	40.9 (37.0–44.9)	52.3 (48.9–55.7)	66.7 (63.6–69.9)	5.8 (5.2–6.4)	7.43
12,000–23,999	27.4 (23.1–31.6)	49.8 (46.7–52.9)	55.2 (51.3–59.1)	68.8 (66.1–71.6)	5.2 (4.5–5.8)	5.20
$\geq 24,000$	33.5 (28.4–38.5)	57.2 (54.1–60.3)	60.4 (56.7–64.1)	70.6 (67.7–73.5)	4.6 (3.9–5.4)	3.56
Refused/ do not know	18.2 (15.2–21.2)	33.3 (29.1–37.5)	46.3 (42.8–49.8)	63.9 (60.7–67.2)	5.7 (5.2–6.3)	9.71
<i>P</i> for difference	<0.001	<0.001	<0.001	<0.001		

Abbreviation: CI=confidence interval; AAPC=average annual percentage change; CNY=Chinese Yuan.

* Annual changes were calculated as the absolute difference in the health examination rate between the start and end years divided by the total number of years covered.

[†] All subgroups below depict the health examination rate within 1 year.

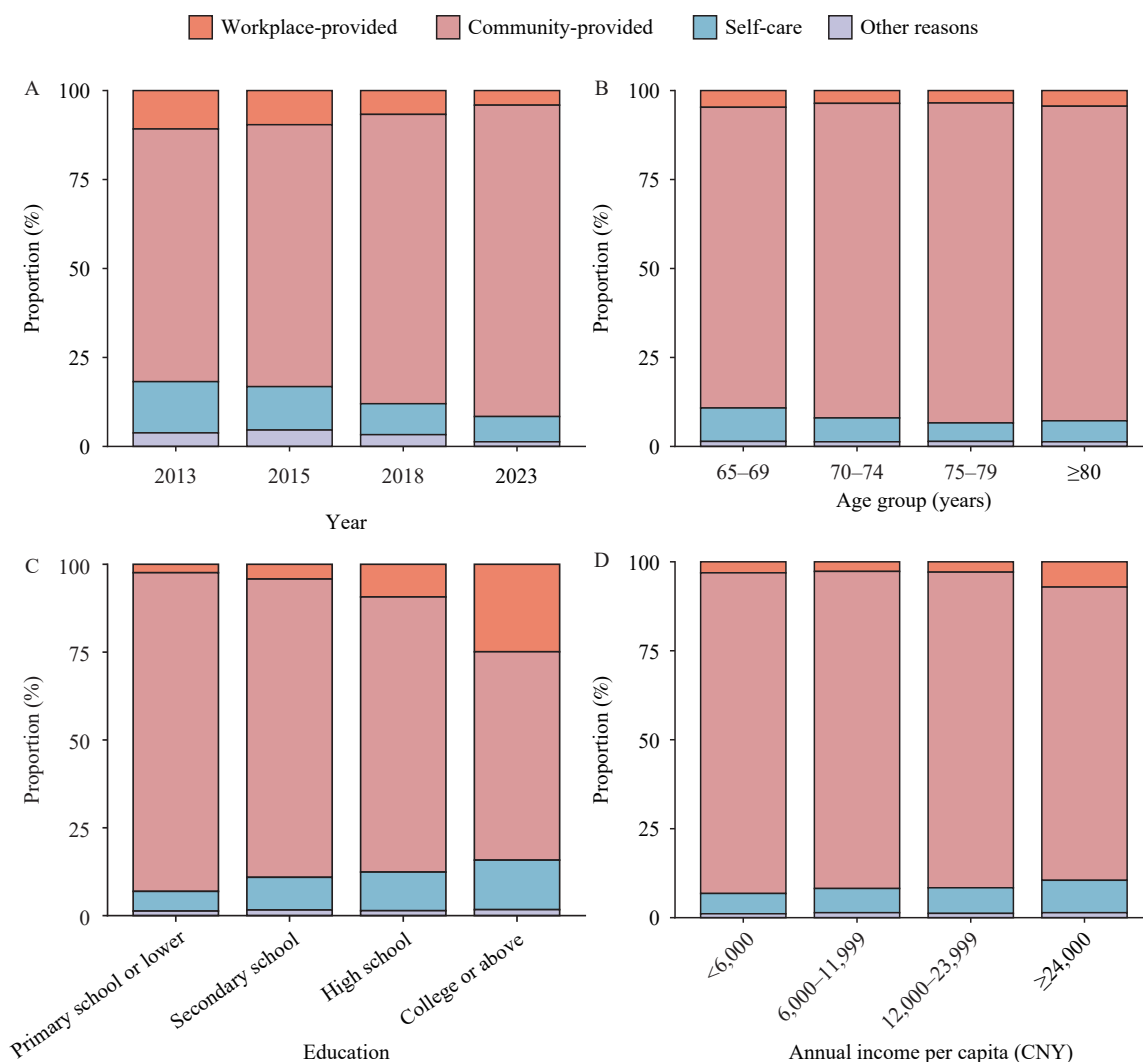


FIGURE 1. Reasons for undergoing health examinations among individuals aged ≥ 65 years in China. (A) by year, 2013–2023; (B) by age group in 2023; (C) by education in 2023; (D) by annual per capita income in 2023.

later in China. Although the value and effectiveness of health examinations in the general population have long been debated, evidence suggests that they are generally not associated with reductions in mortality, cardiovascular events, or cardiovascular disease incidence and might increase false-positive findings and overdiagnosis (8); health examinations for older adults are still recommended by most guidelines (9). The health examination rate varies in different countries; for example, attendance at the National Health Service Health Check Program in England was 52.6% between 2012 and 2017, and the rate in the Saudi Family Health Survey was 49.27% (10). However, few studies have reported the rate of health examinations among older adults.

The substantial increase in the health examination rate among older adults in China observed in the

present study can be largely attributed to the healthcare reforms in China and the gradual improvement in health literacy in the population (11). With the goal of providing of affordable and equitable basic healthcare for all by 2020, China unveiled an ambitious healthcare reform plan in April 2009 and committed to spending an additional 850 billion yuan in the ensuing 3 years (12). In 2009, the State Council of the People's Republic of China issued a notice requiring regular health examinations for adults aged ≥ 65 years (13). Subsequently, the National Health and Family Planning Commission, or later the National Health Commission, implemented the National Basic Public Health Service Program, and further emphasized the need to provide free annual health examinations for adults aged ≥ 65 years (14). Policy attention and financial support directed toward underdeveloped

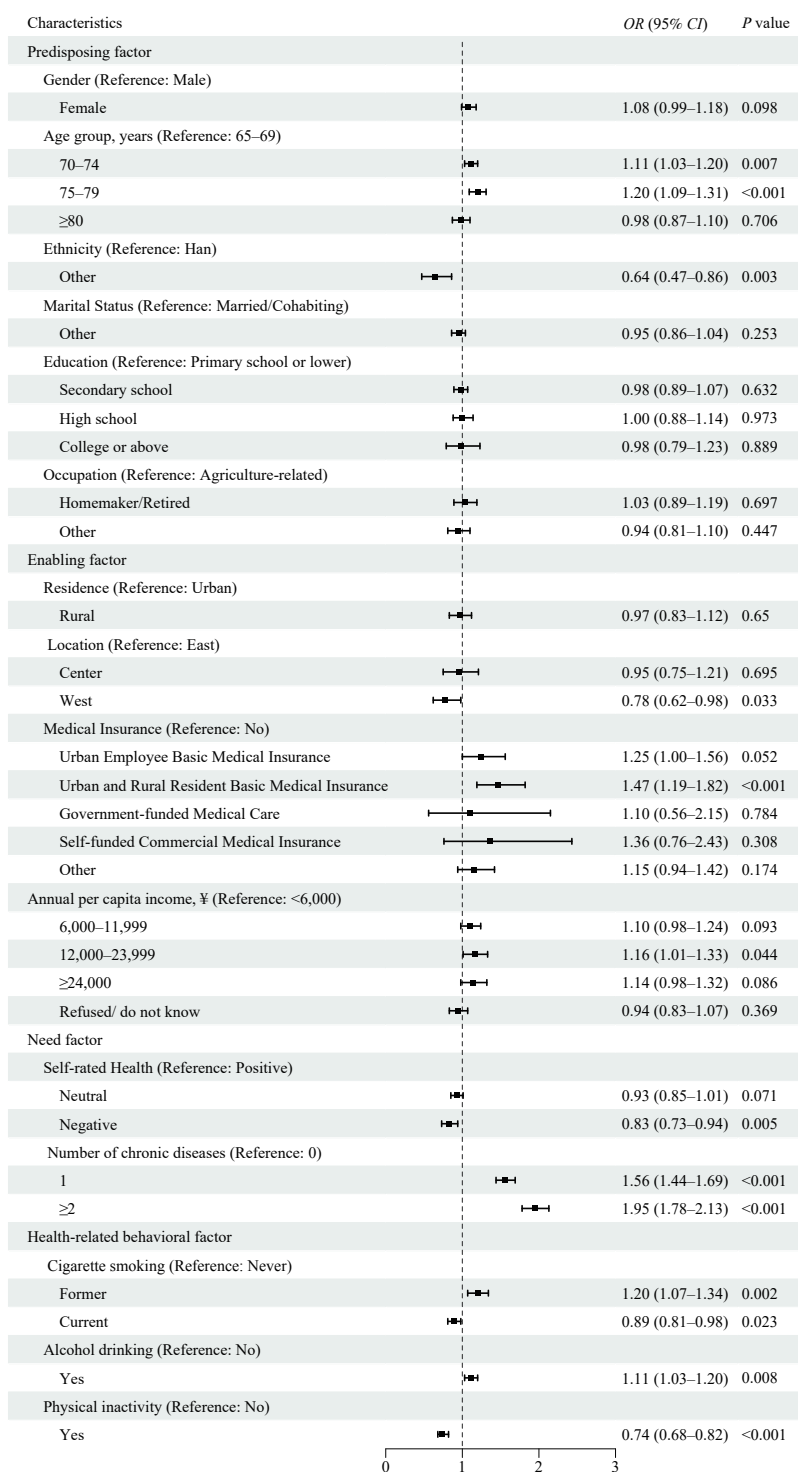


FIGURE 2. Multivariable logistic regression analysis of factors associated with undergoing a health examination among individuals aged ≥ 65 years in China.

Abbreviation: OR=odds ratio; CI=confidence interval.

regions and low-income populations help explain the rapid narrowing of disparities in these areas, as well as why the proportion of free community-provided health examinations is often higher in rural regions. As demonstrated in this study, since then, the overall

health examination rate among older adults has increased substantially, and remarkable progress has been achieved. Nevertheless, it must be acknowledged that a gap remains in achieving full coverage, and continued policy support is required.

Notably, need- and health-related behavioral factors were the most relevant, which is consistent with previous studies (15). Older adults with chronic diseases may have stronger health awareness owing to prolonged exposure to healthcare services. However, individuals with poor self-rated health, insufficient physical activity, and current smokers were less willing to participate in health examinations, which may have been related to lower awareness of health-related behaviors and insufficient health literacy. These findings suggest that targeted health education emphasizing the importance and necessity of health examinations for individuals with relatively poor self-rated health or unhealthy behaviors is warranted to further improve annual health examination coverage.

This study has several limitations. First, the CCDRFS was not intended primarily to examine health examination patterns. Questionnaires were limited to the timing and reason for the most recent examination and did not include information on examination frequency. Furthermore, the self-reported timing of the most recent examination may have been prone to recall bias. Additionally, the Anderson model used in this study includes relatively few variables, particularly those lacking macro-level regional factors, which may have limited its explanatory power.

In conclusion, this study demonstrates a substantial increase in health examination rates in China. However, the current rate falls short of the targets set by the Healthy China Initiative (2019–2030) and the National Basic Public Health Service Program, both of which aim to provide free annual health examinations for adults aged ≥ 65 years. To achieve this target, sustained policies and financial support are necessary to strengthen primary prevention efforts and ensure broader access to health examinations for older adults. However, given the limited resources, priority should be given to targeted health education for older adults with relatively low health awareness.

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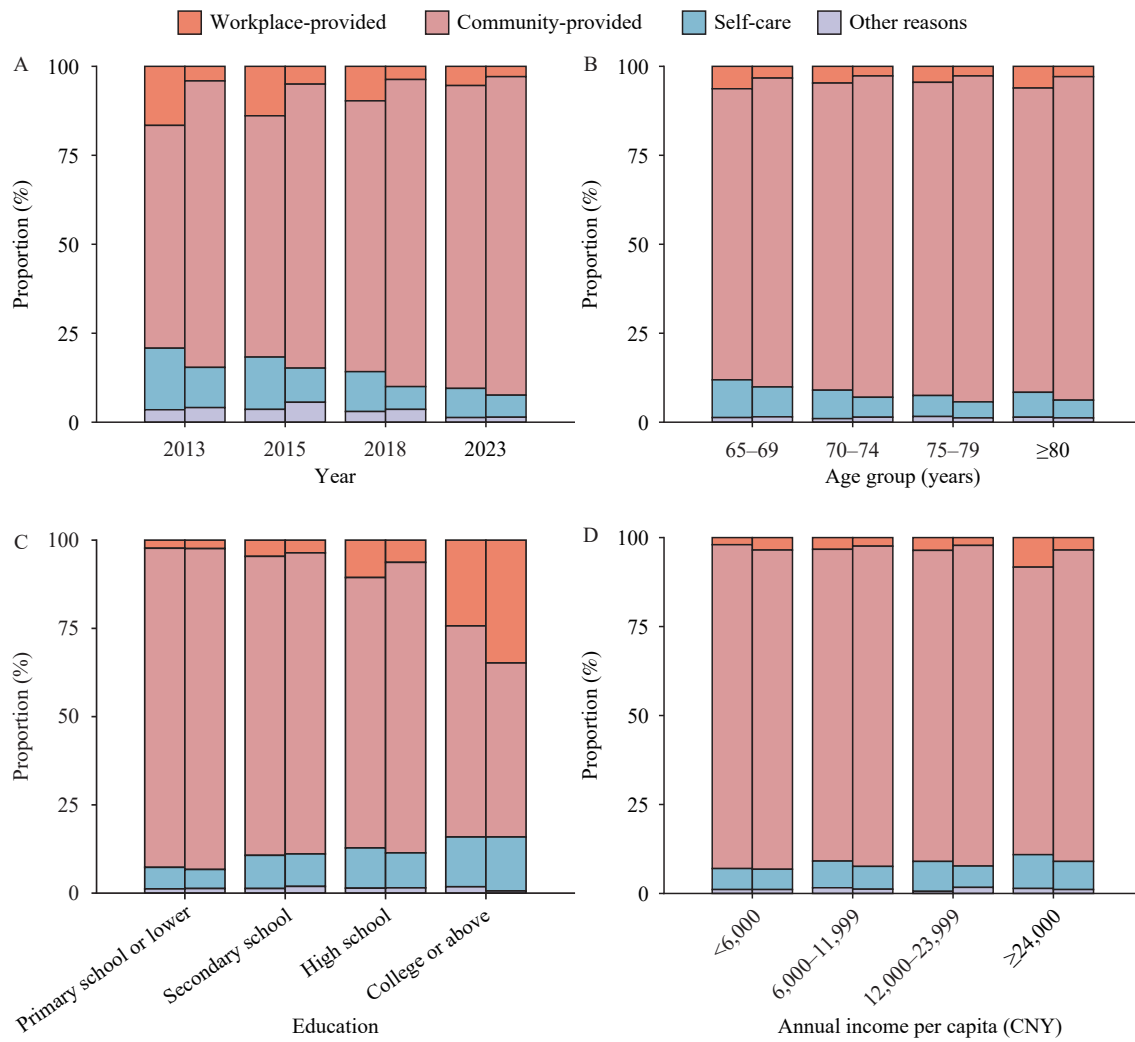
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SUPPLEMENTARY MATERIAL



SUPPLEMENTARY FIGURE S1. Residence-specific reasons for undergoing health examinations among individuals aged ≥ 65 years in China. (A) by year and residence, 2013–2023; (B) by age group and residence in 2023; (C) by education and residence in 2023; (D) by annual per capita income and residence in 2023.

Note: For each category in each chart, the left column represents urban areas, and the right column represents rural areas. Abbreviation: CNY=Chinese Yuan.

SUPPLEMENTARY TABLE S1. General characteristics of individuals aged ≥ 65 years by history of health examination in China, 2023 [No. (%)].

Characteristics	Overall (<i>n</i> =68,011)	Ever underwent a health examination (<i>n</i> =52,923)	Never underwent a health examination (<i>n</i> =15,088)	<i>P</i>
Sex				0.002
Man	32,218 (47.4)	24,899 (47.0)	7,319 (48.5)	
Woman	35,793 (52.6)	28,024 (53.0)	7,769 (51.5)	
Age group, years				<0.001
65–69	29,182 (42.9)	22,188 (41.9)	6,994 (46.4)	
70–74	22,337 (32.8)	17,787 (33.6)	4,550 (30.2)	
75–79	10,936 (16.1)	8,720 (16.5)	2,216 (14.7)	
≥ 80	5,556 (8.2)	4,228 (8.0)	1,328 (8.8)	
Residence				<0.001
Urban	30,903 (45.4)	25,339 (47.9)	5,564 (36.9)	
Rural	37,108 (54.6)	27,584 (52.1)	9,524 (63.1)	
Location				<0.001
East	31,149 (45.8)	24,899 (47.0)	6,250 (41.4)	
Central	16,262 (23.9)	12,847 (24.3)	3,415 (22.6)	
West	20,600 (30.3)	15,177 (28.7)	5,423 (35.9)	
Education				<0.001
Primary school or lower	45,775 (67.3)	35,086 (66.3)	10,689 (70.8)	
Secondary school	14,177 (20.8)	11,146 (21.1)	3,031 (20.1)	
High school	6,431 (9.5)	5,285 (10.0)	1,146 (7.6)	
College or above	1,628 (2.4)	1,406 (2.7)	222 (1.5)	
Ethnicity				<0.001
Han	62,461 (91.8)	49,281 (93.1)	13,180 (87.4)	
Other	5,550 (8.2)	3,642 (6.9)	1,908 (12.6)	
Annual per capita income, CNY				<0.001
<6,000	14,099 (20.7)	10,755 (20.3)	3,344 (22.2)	
6,000–11,999	10,070 (14.8)	7,750 (14.6)	2,320 (15.4)	
12,000–23,999	10,538 (15.5)	8,460 (16.0)	2,078 (13.8)	
$\geq 24,000$	13,325 (19.6)	11,323 (21.4)	2,002 (13.3)	
Refused/ do not know	19,979 (29.4)	14,635 (27.7)	5,344 (35.4)	

Abbreviation: CNY=Chinese Yuan.

Preplanned Studies

Screening Carpal Tunnel Syndrome Risk in Occupational Populations — China, 2018–2023

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Xinwei Guo²; Longlong Ma¹; Xingda Qu¹; Ning Jia^{2,†}

Summary

What is known about this topic?

Carpal tunnel syndrome is a common work-related disorder that is affected by personal, biomechanical, and psychosocial factors. Existing risk assessment methods often lack precision, hindering early intervention. As of August 1, 2025, occupational musculoskeletal disorders were recognized in China, emphasizing the need for effective preventive tools.

What has been added by this report?

This study developed machine learning models to identify carpal tunnel syndrome risk using a national dataset ($n=88,609$). The best model achieved 97.66% (3,130/3,131) accuracy, identifying key factors such as hand pain frequency and lifting load, and enhancing the early identification of high-risk workers.

What are the implications for public health practices?

These findings advocate for the use of data-driven screening tools in occupational health screening to enable early interventions. Employers should prioritize ergonomic improvements and symptom-reporting systems in alignment with China's proactive occupational disease policies.

gradient boosting demonstrated superior performance [recall: 99.97% (3,130/3,131); precision: 84.43% (3,130/3,707)] in identifying high-risk individuals. The SHapley Additive exPlanations (SHAP) analysis revealed that subjective hand pain characteristics were the primary factors, followed by psychosocial stressors, including fatigue and biomechanical exposure.

Conclusion: These findings support the transition toward data-driven public health practices, enabling targeted early prevention and ergonomic interventions to mitigate the burden of CTS in at-risk workforces.

Carpal tunnel syndrome (CTS) has emerged as a critical occupational health challenge owing to the increasing prevalence of repetitive strain injuries in diverse work environments (1). Globally, approximately 14.4% of the population is affected by CTS (1). In China, its prevalence among office workers is 9.6%, which is notably higher than that observed in many Western populations (2). On August 1, 2025, occupational musculoskeletal disorders were officially included in the updated "Classification and Catalog of Occupational Diseases" in China. This major policy milestone places CTS within the scope of statutory occupational disease management, creating an urgent imperative for enterprises and public health authorities to implement effective and legally compliant preventive and control measures.

The etiology of CTS is multifactorial and involves complex interactions among biomechanical exposure (including repetitive hand movements), personal demographics (including age and sex), and psychosocial stressors (3–5). Epidemiological studies have identified specific predictors. For instance, Lund et al. (6) quantified the impact of wrist velocity on the prevalence of CTS, whereas Lee et al. (7) highlighted demographic disparities and noted a high prevalence among middle-aged women. However, traditional

ABSTRACT

Introduction: Carpal tunnel syndrome (CTS) poses a substantial public health burden, necessitating precise early detection strategies that align with the prevention-focused goals of the evolving occupational health policy in China.

Methods: Machine learning algorithms were employed to integrate multidimensional risk factors for CTS screening using a large-scale dataset of 88,609 valid responses, including 10,438 reported CTS cases. The SHapley Additive exPlanations analysis identified the key factors, and ablation tests confirmed the importance of these features.

Results: Among the developed models, extreme

linear statistical methods often fail to capture the nonlinear and high-dimensional interactions among diverse risk factors (8). Consequently, the current screening approaches may lack the sensitivity required for early detection in large-scale occupational populations, representing a critical gap in meeting new prevention-oriented regulatory standards.

To address these limitations, this study applied advanced machine learning algorithms to synthesize multidimensional risk factors into a robust risk

screening framework. By enhancing screening accuracy beyond traditional methods, this study aimed to provide a data-driven foundation for early screening and targeted intervention, thereby supporting the implementation of new occupational health policies and reducing the burden of CTS in the workforce.

Figure 1 presents a schematic overview of the methodology of the study. This study used data from a large-scale national occupational health survey conducted in China between 2018 and 2023. The

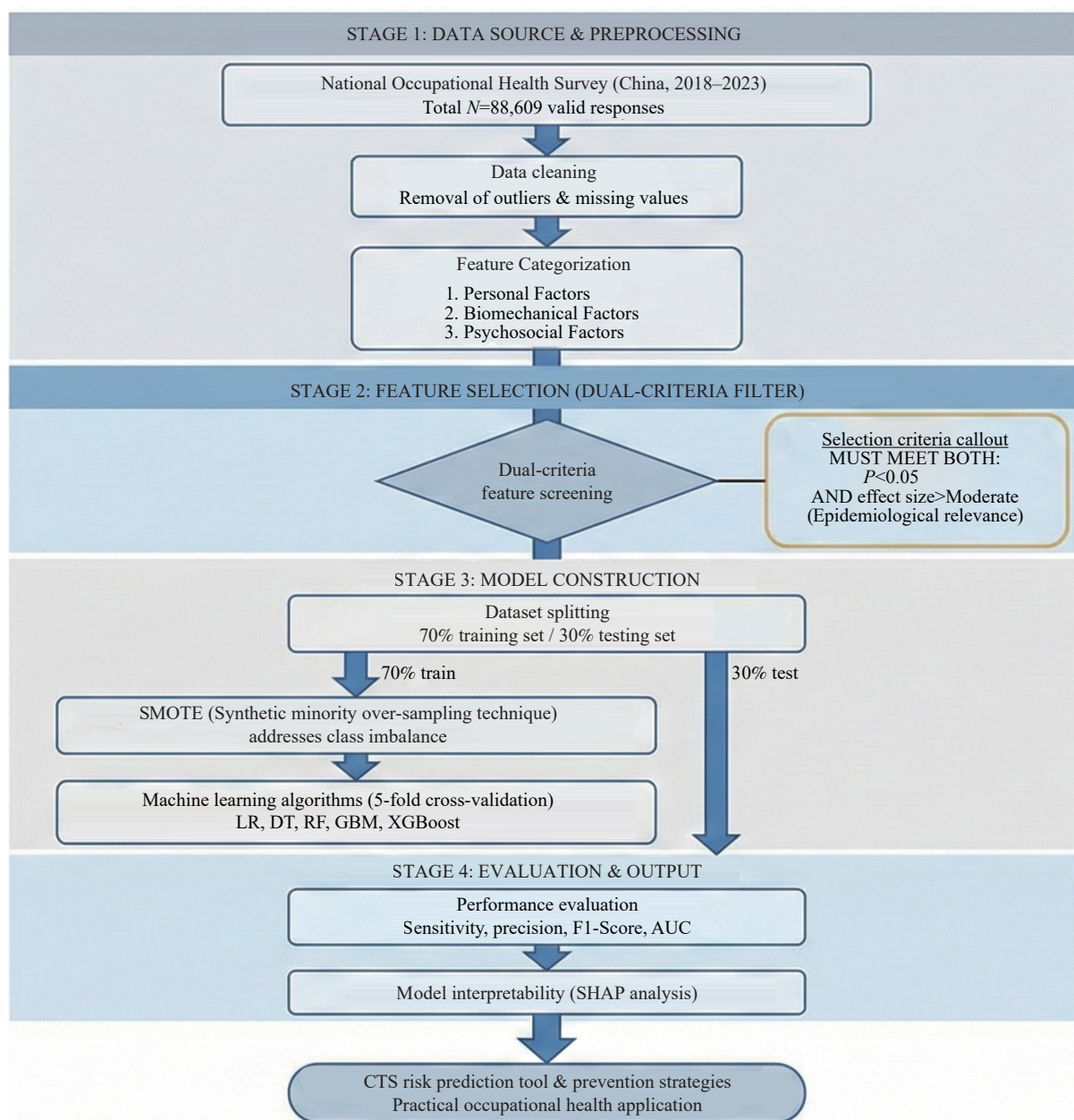


FIGURE 1. Schematic overview of the study methodology.

Abbreviation: LR=logistic regression; DT=decision tree; RF=random forest; GBM=gradient boosting machine; XGBoost=extreme gradient boosting; AUC=area under the ROC-curve; SHAP=SHapley Additive exPlanations.

dataset comprised 88,609 valid responses from workers across nine major industrial sectors and 29 distinct job types (9). A total of 10,438 participants reported CTS, corresponding to an overall prevalence of 11.78% in the study population. Data were collected using the electronic Chinese Musculoskeletal Disorder Questionnaire, integrated into the ergonomic assessment and WMSDs analysis system developed by the National Institute of Occupational Health and Poison Control, Chinese Center for Disease Control and Prevention (10). This study was approved by the Ethics Review Committee of the National Institute of Occupational Health and Poison Control, China. All participants provided informed consent prior to the study.

The primary outcome variable was self-reported CTS status (binary: CTS *vs.* non-CTS). The adoption of a standardized self-report-based CTS is fully aligned with the core objective of this study: to develop a scalable, high-efficiency risk-screening tool for large-scale occupational populations. To build a robust multidimensional screening model, potential risk factors were stratified into three domains: 1) personal factors (demographics, BMI, and exercise habits), 2) biomechanical factors (repetitive movements, force exertion, and posture), and 3) psychosocial factors (job demands and task load). Data preprocessing involved rigorous cleaning (removal of outliers and missing values) and encoding (standardization of continuous variables and ordinal or one-hot encoding of categorical variables). To ensure that the developed tool focused on practically meaningful risk factors rather than statistical noise, a dual-criteria feature-selection strategy was applied. Statistical tests (t-tests, chi-square tests, or nonparametric equivalents) were paired with effect size analyses. Only risk factors demonstrating both statistical significance ($P < 0.05$) and moderate to strong effect sizes ($\phi > 0.1$, $|r| > 0.25$, $\varepsilon^2 > 0.06$) were retained as input features for the machine learning models. Statistical analyses were performed using SPSS (version 19.0, IBM Corp., Armonk, NY, USA).

Five machine learning algorithms — binary logistic regression, decision tree, random forest, gradient boosting, and extreme gradient boosting (XGBoost) — were developed to screen CTS risk. These models were selected for their capacity to handle nonlinear interactions inherent in occupational exposure data. The dataset was partitioned into training [70% (62,026/88,609)] and testing [30% (26,583/88,609)] sets. To address typical class imbalance in occupational

disease data, the synthetic minority oversampling technique (SMOTE) was applied to the training set. The train-test split was performed at the beginning of the pipeline. All data-dependent procedures were performed exclusively within the training partitions. The held-out test set remained fully separate throughout all preprocessing and tuning steps to eliminate information leakage and ensure unbiased performance estimates.

SHapley Additive exPlanations (SHAP) values were used to identify the most relevant risk factors and to guide early intervention strategies. The model performance was evaluated using metrics prioritized for public health screening utility. While accuracy provides an overall baseline, emphasis is placed on sensitivity (recall) and the F1 score. High sensitivity is critical in occupational health surveillance to minimize false negatives (missed screenings) and ensure that high-risk workers receive timely ergonomic interventions. Precision was monitored to reduce false positives and unnecessary resource utilization. The area under the receiver operating characteristic curve was calculated to assess the discriminative power of the models across all classification thresholds.

SHAP analysis identified a clear hierarchy of risk factors and actionable targets for occupational CTS prevention (Table 1). Three risk tiers were proposed based on SHAP predictive weight, modifiability, and functional role in occupational CTS prevention. Tier 1: Core symptoms comprised the top-ranked hand pain and symptom variables with dominant explanatory power, serving as high-yield primary screening signals for identifying at-risk workers. Tier 2: Modifiable factors included psychosocial fatigue and biomechanical workload factors of moderate importance, representing the only intervention-actionable targets for workplace ergonomic optimization and fatigue management. Tier 3: Background covers stable personal and occupational factors, such as job tenure and general health, with small but consistent screening contributions used for baseline risk stratification rather than direct intervention. Subjective hand pain characteristics emerged as the strongest screening signals, with pain frequency and duration ranking as the top two contributors to model accuracy. Among the modifiable occupational risk factors, fatigue perception (psychosocial domain) and cumulative lifting load (biomechanical domain) demonstrated the highest importance, followed by repetitive hand movements and non-neutral wrist postures. Personal demographic

TABLE 1. Ranking of the top ten factors for carpal tunnel syndrome based on mean SHAP values and proposed risk tiers.

Rank	Factors	Category	Mean SHAP	Proposed risk tier
1	Frequency of hand pain/discomfort	Personal	2.029	Tier 1: Core Symptom
2	Hand pain/discomfort in past 12 months	Personal	1.356	Tier 1: Core Symptom
3	Tenure (years) in current job	Personal	0.053	Tier 3: Background
4	Physical health status	Personal	0.047	Tier 3: Background
5	Physical exercise	Personal	0.022	Tier 3: Background
6	Hand pain/discomfort in past 7 days	Personal	0.016	Tier 1: Core Symptom
7	Feel fatigue	Psychosocial	0.013	Tier 2: Modifiable
8	Hours until feeling fatigued	Psychosocial	0.013	Tier 2: Modifiable
9	Cumulative lifting load	Biomechanical	0.009	Tier 2: Modifiable
10	Duration of hand symptoms (Annual)	Personal	0.009	Tier 1: Core Symptom

Abbreviation: SHAP=SHapley Additive exPlanations.

factors, including age and sex, showed moderate but consistent contributions. This factor ranking directly informs workplace prevention strategies that should prioritize systematic symptom monitoring, fatigue management, and physical load reduction as core intervention components.

Statistical screening initially identified 26 significant factors spanning the personal, biomechanical, and psychosocial domains (Supplementary Table S1, available at <https://weekly.chinacdc.cn/>). Ablation testing further confirmed the fundamentally multidimensional nature of CTS risk. Removing any single factor domain, including psychosocial factors, resulted in a notable degradation in the model screening performance (Figure 2). This finding validates the necessity of integrated multidomain occupational health surveillance rather than single-factor risk monitoring.

Among the five machine learning algorithms

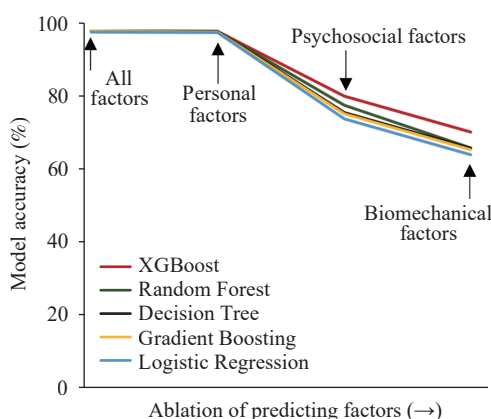


FIGURE 2. Model accuracy decreased with the ablation of the screening factors.

Abbreviation: XGBoost=extreme Gradient Boosting.

evaluated, XGBoost emerged as the optimal model for large-scale occupational CTS screening (Supplementary Table S2, available at <https://weekly.chinacdc.cn/>). It achieved near-perfect sensitivity [99.97% (3,130/3,131)], which is critical for minimizing false negatives in public health surveillance, while maintaining high precision [84.43% (3,130/3,707)] and robust discriminative power, with an area under the receiver operating characteristic curve of 0.992 (Supplementary Figure S1, available at <https://weekly.chinacdc.cn/>). Although the decision tree also achieved a high recall, XGBoost delivered the most balanced performance between case detection capability and screening reliability for population-level screening applications.

DISCUSSION

This study aimed to develop and validate a generalizable high-performance machine learning screening model for CTS risk screening to support large-scale universal occupational health surveillance. The analytical framework of this study is strictly aligned with this objective. By synthesizing multidimensional risk factors using machine learning, this study established a high-precision risk-screening framework for CTS in occupational populations. The XGBoost model demonstrated superior risk-screening performance, particularly in terms of sensitivity (99.97%), ensuring minimal false-negative results during mass screening. SHAP analysis further identified subjective hand pain characteristics, fatigue perception, and biomechanical load as primary risk factors, validating the multifactorial etiology of CTS.

These findings have profound public health

implications, particularly following the inclusion of musculoskeletal disorders in China's "Classification and Catalog of Occupational Diseases." First, the dominance of hand pain symptoms provided strong evidence for the establishment of symptom-based active sentinel monitoring. This approach offers a low-cost, direct pathway for early detection that is superior to passive reliance on clinical screening. Second, identifying fatigue as a critical factor bridges the gap between psychosocial stress and physical damage. This finding underscores the fact that effective CTS control requires the management of organizational factors, such as work rhythm, directly aligning with the Healthy China 2030 initiative's requirements for occupational stress management. Ultimately, this model serves as a quantifiable risk-grading tool, facilitating a paradigm shift in occupational health management from post-diagnosis compensation to pre-diagnosis prevention.

This study was limited by its cross-sectional design. The core screening variables of the established SHAP-based screening model were predominantly hand pain- and discomfort-related indicators extracted from the cross-sectional survey data, including the subjective pain frequency and duration. These symptomatic variables substantially overlapped with the symptomatic definition of self-reported CTS, which may partially account for the excellent screening performance of our model. This overlap indicates that the model primarily achieves symptom-based CTS identification rather than a definitive diagnosis. Furthermore, this study prioritized discrimination metrics for occupational health risk stratification and did not perform a formal calibration analysis. Future research should include calibration plots and Brier score evaluations to validate the reliability of the predicted risks and better support real-world decision-making.

From a practical application perspective, the proposed model was developed for the preliminary population-level screening of suspected carpal tunnel syndrome (CTS) in occupational health practice. It aims to support the early identification of at-risk workers and guide targeted follow-up arrangements and is not intended to serve as a standalone diagnostic tool. The definitive diagnosis of CTS still relies on formal specialist clinical assessment combined with objective electrophysiological examinations, such as nerve conduction studies, which remain the diagnostic gold standard.

The developed machine learning models can also

support targeted employer interventions. For example, employers should establish nonpunitive, rapid symptom-reporting mechanisms (such as "one-click reporting" via mobile applications). Reports of frequent hand pain should serve as immediate triggers for on-site ergonomic investigations. Furthermore, to address the critical risks associated with fatigue and insufficient rest, enterprises should implement structured microbreak policies and optimize work pacing to prevent continuous high-intensity exposure. For the risks associated with cumulative lifting loads, priority should be given to engineering controls, such as introducing assistive handling devices and optimizing the workstation height to minimize non-neutral wrist postures.

These findings provide a scientific basis for refining screening and prevention standards for occupational CTS and guide the allocation of work injury prevention funds. Future initiatives should focus on the longitudinal validation of these models across diverse industries to establish causal relationships. Policymakers can use these data-driven insights to formulate ergonomic exposure limits that are suitable for the Chinese industrial context.

Conflicts of interest: No conflicts of interest.

Ethical statement: Approved by the Ethics Review Committee of the National Institute of Occupational Health and Poison Control, China. All participants provided informed consent prior to their inclusion in the study.

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SUPPLEMENTARY MATERIALS

SUPPLEMENTARY TABLE S1. Predictors selected for machine learning model development: results of statistical screening ($n=88,609$).

Category	Risk factors	Data type	P	Effect size	Selected
Personal Factors	Gender	Binary	0.001	0.011	No
	Age	Continuous	<0.001	0.091	No
	Height	Continuous	0.136	0.028	No
	Weight	Continuous	0.003	0.016	No
	BMI	Continuous	0.020	0.003	No
	Physical exercise	Ordinal	<0.001	0.121	Yes
	Smoking history	Ordinal	<0.001	0.002	No
	Number of cigarettes smoked	Continuous	0.042	0.033	No
	Years since quitting smoking	Continuous	0.631	0.010	No
	Physical health status	Ordinal	<0.001	0.224	Yes
	Whether having traumatic disease/injury	Binary	<0.001	0.028	No
	Previous disease history	Binary	<0.010	0.004	No
	Tenure (years) in current job	Continuous	0.034	0.261	Yes
	Total work tenure (years)	Continuous	<0.001	0.140	No
	Hand pain/discomfort in past 7 days	Binary	0.011	0.390	Yes
	Hand pain/discomfort in past 12 months	Binary	<0.001	0.701	Yes
	Frequency of hand pain/discomfort	Ordinal	<0.001	0.814	Yes
	Duration of hand symptoms (Annual)	Ordinal	<0.001	0.509	Yes
	Hand pain score	Ordinal	<0.001	0.452	Yes
Biomechanical Factors	Lifting heavy objects (>5 kg each time)	Ordinal	<0.001	0.012	No
	Lifting very heavy objects (>20 kg each time)	Ordinal	<0.001	0.009	No
	Cumulative lifting load	Continuous	<0.001	0.290	Yes
	Work requiring upper limb/hand force	Ordinal	<0.001	0.031	No
	Using vibrating tools at work	Ordinal	<0.001	0.144	Yes
	Driving vehicles	Ordinal	0.142	0.081	No
	Working in uncomfortable postures	Ordinal	<0.001	0.212	Yes
	Work requires multiple repetitive motions per minute	Binary	<0.001	0.141	Yes
	Wrists frequently bend upward/downward	Binary	<0.001	0.163	Yes
	Wrists need to be bent for prolonged periods	Binary	<0.001	0.191	Yes
	Wrists frequently rest on hard, angled edges	Binary	<0.001	0.138	Yes
	Work requires pinching/gripping items/tools	Binary	<0.001	0.130	Yes
	Hand position during work	Binary	<0.001	0.025	No

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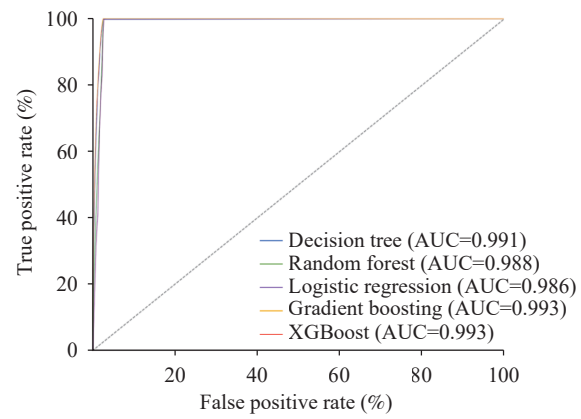
Category	Risk factors	Data type	P	Effect size	Selected
Psychosocial Job Factors	Doing almost the same work every day	Binary	0.010	0.071	No
	Work requirement changes daily	Binary	0.023	0.009	No
	Work rotation between you and colleagues	Binary	0.063	0.021	No
	Feel fatigue	Binary	0.011	0.202	Yes
	Levels of fatigue perception	Ordinal	<0.001	0.181	Yes
	Hours until feeling fatigued	Continuous	<0.001	0.381	Yes
	Number of work days per week	Continuous	<0.001	0.012	No
	Number of work hours per day	Continuous	<0.001	0.133	Yes
	Work shift conditions	Ordinal	<0.001	0.044	No
	Frequently working overtime	Binary	<0.001	0.083	No
	Number of work breaks per shift (times)	Continuous	0.271	0.112	Yes
	Total break time per shift (minutes)	Continuous	0.111	0.201	Yes
	Sufficient break time	Binary	<0.001	0.151	Yes
	Returning to work after breaks	Binary	<0.001	0.020	No
	Can decide when to start and end work	Binary	<0.001	0.033	No
	Can decide when to take breaks	Binary	<0.001	0.049	No
	Work department is understaffed	Binary	<0.001	0.110	No
	Frequently covering shifts for colleagues	Binary	<0.001	0.691	Yes
	Engaged in other jobs	Binary	<0.001	0.016	No
	Experiencing elbow fatigue	Binary	0.011	0.131	No
	Number of elbow fatigue per month	Continuous	<0.001	0.370	No
	Experiencing hand fatigue	Binary	<0.001	0.348	No
	Number of hand fatigue per month	Continuous	<0.001	0.743	No

Abbreviation: BMI=body mass index.

SUPPLEMENTARY TABLE S2. Ranking of the top ten predictors for carpal tunnel syndrome based on mean SHAP values and proposed risk tiers.

Rank	Predictor	Category	Mean SHAP	Proposed Risk Tier
1	Frequency of hand pain/discomfort	Personal	2.029	Tier 1: Core Symptom
2	Hand pain/discomfort in past 12 months	Personal	1.356	Tier 1: Core Symptom
3	Tenure (years) in current job	Personal	0.053	Tier 3: Background
4	Physical health status	Personal	0.047	Tier 3: Background
5	Physical exercise	Personal	0.022	Tier 3: Background
6	Hand pain/discomfort in past 7 days	Personal	0.016	Tier 1: Core Symptom
7	Feel fatigue	Psychosocial	0.013	Tier 2: Modifiable
8	Hours until feeling fatigued	Psychosocial	0.013	Tier 2: Modifiable
9	Cumulative lifting load	Biomechanical	0.009	Tier 2: Modifiable
10	Duration of hand symptoms (Annual)	Personal	0.009	Tier 1: Core Symptom

Abbreviation: SHAP=SHapley Additive exPlanations.



SUPPLEMENTARY FIGURE S1. ROC curves and AUC of the machine learning models.

Abbreviation: ROC=receiver operating characteristic; AUC=area under the ROC-curve; XGBoost=extreme Gradient Boosting.

Preplanned Studies

Comparison of Work-related Musculoskeletal Disorders Between Flight Attendants and National Occupational Populations — China, 2018–2023

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Summary

What is already known about this topic?

The risk of work-related musculoskeletal disorders (WMSDs) differs by industry. Flight attendants in China show a high prevalence of upper-limb WMSDs.

What is added by this report?

Compared with the National Occupational Group and Comparable Industry Subgroup, flight attendants had a higher prevalence of neck, shoulder, and lower back WMSDs. After adjustment for demographic, ergonomic, and work-organization factors using generalized linear mixed models, flight attendant occupation was not significantly associated with WMSDs compared with the Comparable Industry Subgroup (adjusted odds ratio=0.76, 95% confidence interval: 0.43, 1.34).

What are the implications for public health practice?

Prevention efforts can target modifiable ergonomic and work-organization factors, including cabin ergonomics, staffing, rest opportunities, and autonomy over work breaks.

mixed models were used.

Results: The prevalence of WMSDs (51.01%, 684/1,341) in flight attendants was higher than that in the National Occupational Group (37.31%, 32,563/87,268) and Comparable Industry Subgroup (45.46%, 7,376/16,224) ($P<0.001$), particularly in the neck, shoulders, and lower back. After adjustment for demographic, ergonomic, and work-organization factors, flight attendant occupation was not significantly associated with WMSDs compared with the Comparable Industry Subgroup. Working in uncomfortable postures, repetitive trunk movements, prolonged fixed-neck or bent-head postures, and working >8 h/day were associated with higher odds of developing WMSDs, whereas sufficient rest time and male sex were associated with lower odds.

Conclusion: Prevention efforts against WMSDs among flight attendants should consider improvements to cabin ergonomics, work scheduling, rest opportunities, and autonomy during work breaks.

ABSTRACT

Introduction: This study compared the prevalence of work-related musculoskeletal disorders (WMSDs) between civil aviation flight attendants and the national occupational population in China.

Methods: Data were obtained from a national cross-sectional survey conducted from 2018 to 2023, including 88,609 workers from 29 industries. Overall, 1,341 flight attendants were compared with the National Occupational Group ($n=87,268$) and a Comparable Industry Subgroup ($n=16,224$) selected from industries with >50% female workers and light-to-moderate physical workloads. Chi-square tests, multivariate logistic regression, and generalized linear

Work-related musculoskeletal disorders (WMSDs) are closely associated with adverse ergonomic exposures and represent a major global occupational health concern linked to substantial productivity loss, absenteeism, and increased workplace costs (1). The 2025 update of the Classification and Catalog of Occupational Diseases of China includes WMSDs as a new major category, thereby underscoring their significance. National occupational health surveillance data have identified civil aviation flight attendants as a high-risk group for WMSDs, with the age-standardized prevalence of upper extremity WMSDs in this population reaching 32.5%, ranking third among 21 major industries (2). Previous studies have reported high levels of WMSDs or musculoskeletal symptoms among aviation-related personnel, including female

Chinese flight attendants, long-haul international flight attendants, and flight security personnel (3–5).

Despite growing evidence of a higher WMSDs burden among flight attendants, research gaps remain. National occupational health surveys have historically focused on traditional manufacturing and heavy industries, leaving WMSDs in the aviation sector less thoroughly investigated (2). It remains unclear whether the increased prevalence among flight attendants is closely related to distinctive occupational exposures or broader demographic and socioeconomic characteristics. Therefore, direct comparison with national occupational populations, including similar industries, is needed to identify industry-specific factors associated with WMSDs and inform tailored preventive strategies.

Data were obtained from the National Occupational Epidemiological Survey, a national cross-sectional study conducted in China between 2018 and 2023 (6). The survey included 88,609 active employees from 29 key industries across seven major geographic regions and nine national economic sectors: agriculture, mining, manufacturing, utilities, construction, trade, transportation, residential services, and health and social work. A stratified cluster sampling design was used to enhance representativeness. Industries were stratified according to their relevance to WMSDs, occupational population size, and national economic importance following the national occupational health monitoring framework. Representative enterprises were selected within each stratum and categorized as large (16.33%, 72/441), medium (10.88%, 48/441), small (41.27%, 182/441), or micro (31.52%, 139/441) enterprises. All on-duty workers at the selected enterprises were invited to participate.

Participants were eligible if they were aged ≥ 18 years and had worked in their current position for at least one year; those with congenital spinal deformities, a history of trauma, or non-occupational musculoskeletal disorders were excluded. Data were collected using a quality-controlled electronic questionnaire. Of the 91,560 respondents, 88,609 provided valid responses, with a response rate of 96.8%.

Furthermore, 1,341 civil aviation flight attendants were included in the study group, and the remaining 87,268 workers in other occupations were assigned to the National Occupational Group. An additional Comparable Industry Subgroup was constructed to improve comparability by selecting industries with a female workforce proportion of $>50\%$ and a light-to-moderate physical workload (Figure 1). This subgroup

included 16,224 participants from packaging and other printing services, healthcare, footwear manufacturing, toy manufacturing, and pharmaceutical manufacturing industries.

Following the guidelines of the National Institute for Occupational Safety and Health (NIOSH), WMSDs were defined as the presence of discomfort (e.g., pain, stiffness, burning, numbness, or tingling) that met the following criteria: occurrence within the past year, onset after starting the current job, no history of accidents or acute injuries affecting the specific site, and monthly frequency or duration exceeding one week. The anatomical regions were categorized as the neck, lower limbs (the hips, knees, and ankles), upper limbs (the shoulders, elbows, and wrists), and trunk (upper and lower back).

Statistical analyses were performed using SPSS (version 26.0, Armonk, NY, USA). Between-group comparisons of categorical variables were conducted using the chi-square or Fisher's exact tests, as appropriate. Variables that were significant in the univariate analyses ($P < 0.05$) were included in the multivariate logistic regression models. Generalized linear mixed models with a binomial distribution, logit link, and random intercepts for province-industry-workplace combinations were used to account for

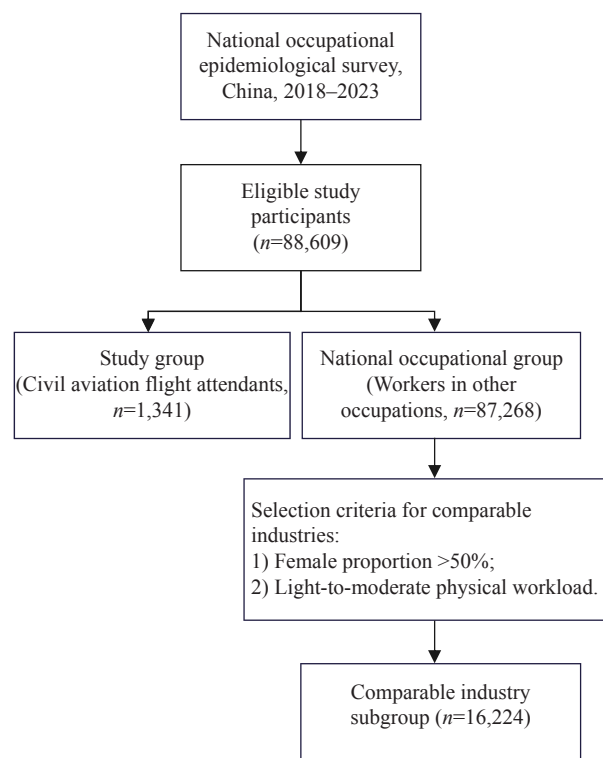


FIGURE 1. Flowchart of study population selection and group classification.

clustering. Results are reported as adjusted odds ratios (aORs) and 95% confidence intervals (CIs), with two-tailed $P < 0.05$ considered statistically significant.

The overall prevalence of WMSDs was 51.01% (684/1,341, standardized: 51.47%) among flight attendants, higher than 37.31% (32,563/87,268, standardized: 36.66%) in the National Occupational Group and 45.46% (7,376/16,224, standardized: 44.57%) in the Comparable Industry Subgroup (all $P < 0.001$) in Figure 2 and Supplementary Table S1 (available at <https://weekly.chinacdc.cn/>). Flight attendants also had a significantly higher prevalence of neck, shoulder, and lower back WMSDs than both reference groups (all $P < 0.05$). The demographic and key occupational characteristics of the three groups are listed in Table 1, and detailed work posture profiles are listed in Supplementary Table S2 (available at <https://weekly.chinacdc.cn/>).

Generalized linear mixed models were used to identify the factors associated with WMSDs in any body region among flight attendants and workers in a Comparable Industry Subgroup (Figure 3). After adjustment for demographic, ergonomic, and work-organization factors and clustering by province-industry-workplace, being a flight attendant was not

significantly associated with WMSDs compared with being in the Comparable Industry Subgroup (aOR=0.76, 95% CI: 0.43, 1.34). In the combined study population, working in uncomfortable postures was associated with higher odds of WMSDs, with aORs of 1.73, 2.31, and 2.10 for sometimes, often, and very frequently, respectively. Other associated factors included repetitive truncal movements (aOR=1.24), prolonged fixed-neck posture (aOR=1.23), prolonged bent-head posture (aOR=1.18), and working >8 h/day (aOR=1.15). Sufficient rest time and male sex were associated with lower odds of developing WMSDs (aOR=0.72 for both). Stratified analyses by sex, rest time, and daily working hours showed generally consistent patterns, and no significant interaction was observed between occupation group and working in uncomfortable postures ($P > 0.05$).

Region-specific multivariate logistic regression analyses restricted to flight attendants showed that female sex, working in uncomfortable postures, and working >8 h/day were associated with higher odds of developing WMSDs across anatomical regions. Sufficient rest was associated with lower odds of WMSDs in the neck, trunk, and any-region models. Understaffing was associated with higher odds of neck

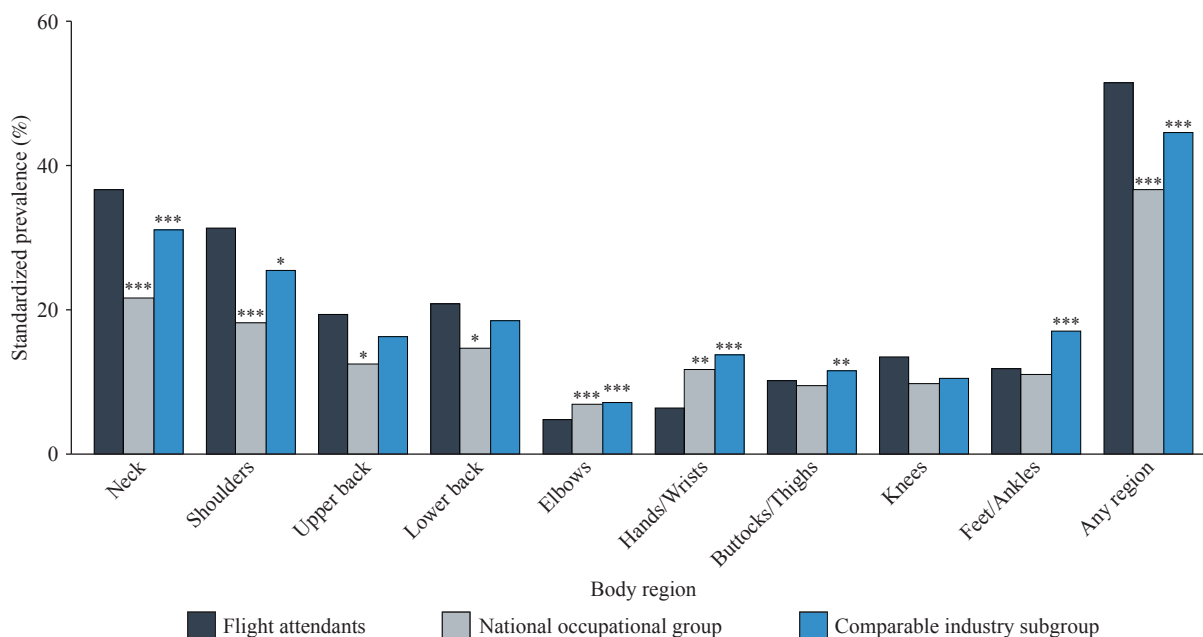


FIGURE 2. Standardized prevalence of work-related musculoskeletal disorders (WMSDs) by body region among flight attendants and comparison groups.

Note: Bars show the standardized prevalence of WMSDs by body region among flight attendants, the National Occupational Group, and the Comparable Industry Subgroup. The standardized prevalence was calculated based on the age distribution of the 18–60-year-old population in China's seventh national population census. Statistical significance was determined by comparison with the flight attendant group as the reference.

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ compared with the flight attendant group (reference).

TABLE 1. Demographic characteristics and key occupational factors among flight attendants and comparison groups, China, 2018–2023.

Variable	Flight attendants (n=1,341) (%)	National occupational group (n=87,268) (%)	Comparable industry subgroup (n=16,224) (%)
Sex			
Men	295 (22.00)	59,694 (68.40)***	3,964 (24.43)*
Women	1,046 (78.00)	27,574 (31.60)	12,260 (75.57)
Age group (years)			
<25	335 (24.98)	14,014 (16.06)***	4,918 (30.31)***
25–34	837 (62.42)	33,499 (38.39)	3,214 (19.81)
35–44	120 (8.95)	22,052 (25.27)	4,973 (30.65)
≥45	49 (3.65)	17,703 (20.29)	3,119 (19.22)
Service duration (years)			
<5	684 (51.01)	43,780 (50.17)***	6,781 (41.80)***
5–9	372 (27.74)	20,336 (23.30)	4,629 (28.53)
10–14	186 (13.87)	13,177 (15.10)	2,684 (16.54)
≥15	99 (7.38)	9,975 (11.43)	2,130 (13.13)
Prolonged standing at work			
Rarely/never	47 (3.50)	14,275 (16.36)***	3,868 (23.84)***
Sometimes	206 (15.36)	20,487 (23.48)	4,923 (30.34)
Often	572 (42.65)	28,593 (32.76)	4,441 (27.37)
Very frequently	516 (38.48)	23,913 (27.40)	2,992 (18.44)
Prolonged squatting/kneeling at work			
Rarely/never	311 (23.19)	53,205 (60.97)***	11,017 (67.91)***
Sometimes	477 (35.57)	23,968 (27.46)	4,036 (24.88)
Often	348 (25.95)	6,828 (7.82)	831 (5.12)
Very frequently	205 (15.29)	3,267 (3.74)	340 (2.10)
Carrying objects >5 kg at work			
Rarely/never	128 (9.55)	32,042 (36.72)***	7,699 (47.45)***
Sometimes	462 (34.45)	31,456 (36.05)	5,995 (36.95)
Often	471 (35.12)	15,745 (18.04)	1,787 (11.01)
Very frequently	280 (20.88)	8,025 (9.20)	743 (4.58)
Working in uncomfortable postures			
Rarely/never	258 (19.24)	41,803 (47.90)***	7,984 (49.21)***
Sometimes	581 (43.33)	31,626 (36.24)	5,538 (34.13)
Often	329 (24.53)	9,135 (10.47)	1,873 (11.54)
Very frequently	173 (12.90)	4,704 (5.39)	829 (5.11)
Sufficient rest time			
Yes	369 (27.52)	44,858 (51.40)***	7,408 (45.66)***
No	972 (72.48)	42,410 (48.60)	8,816 (54.34)
Autonomy over work breaks			
Yes	61 (4.55)	19,335 (22.16)***	2,616 (16.12)***
No	1,280 (95.45)	67,933 (77.84)	13,608 (83.88)
Department understaffing			
Yes	734 (54.74)	37,872 (43.40)***	8,557 (52.74)
No	607 (45.26)	49,396 (56.60)	7,667 (47.26)

Abbreviation: WMSDs=work-related musculoskeletal disorders.

* $P<0.05$, *** $P<0.001$ compared with the flight attendant group (reference).

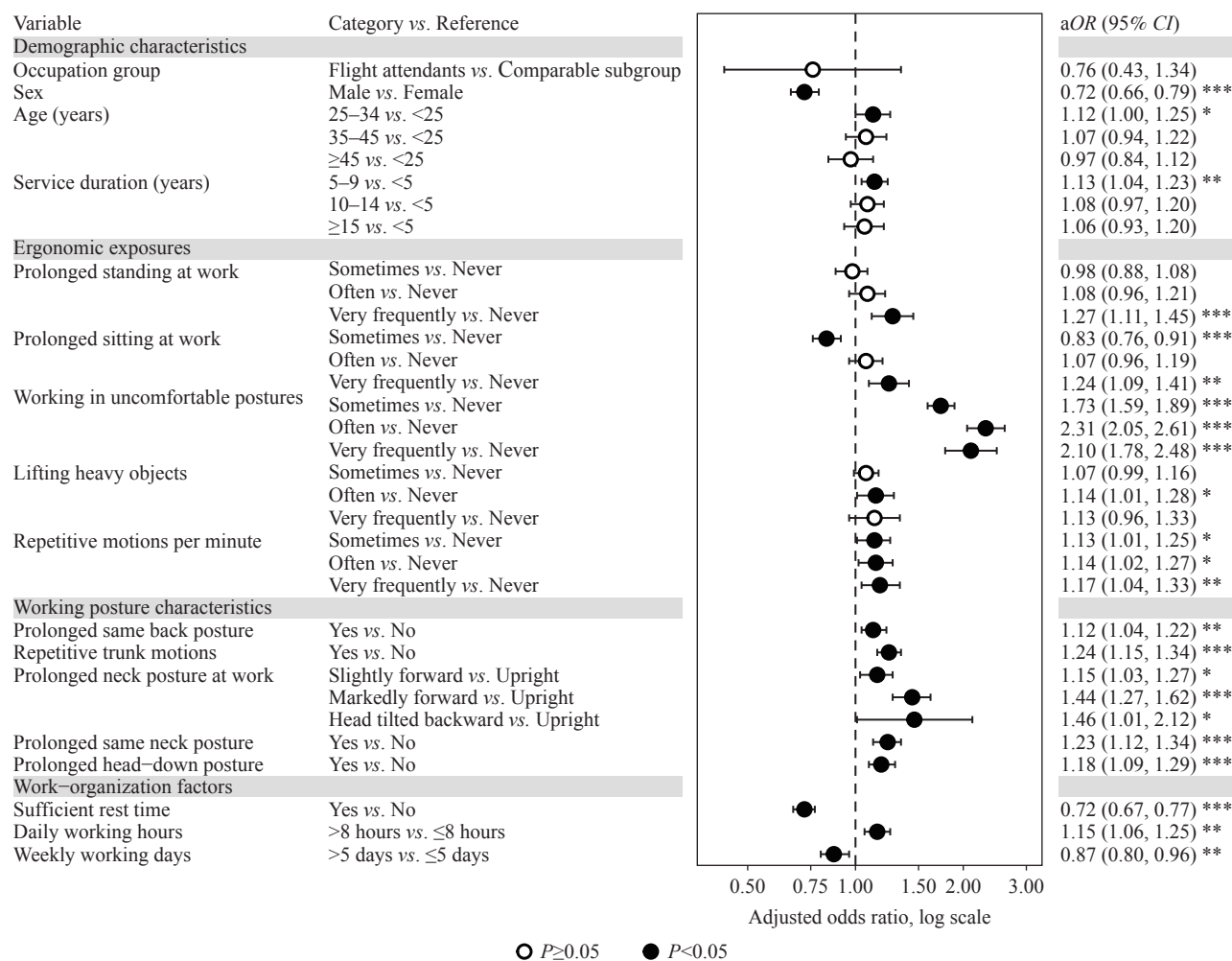


FIGURE 3. Adjusted odds ratios for factors associated with work-related musculoskeletal disorders (WMSDs) in the generalized linear mixed model.

Note: The forest plot shows the adjusted odds ratios (aORs) and 95% confidence intervals (CIs) for factors associated with WMSDs in any body region among flight attendants and workers in the Comparable Industry Subgroup. The generalized linear mixed model included fixed effects for demographic characteristics, ergonomic exposures, and work-organization factors, with a random intercept specified for the combination of province, industry, and workplace. The dashed vertical line indicates an aOR of 1.0.

and upper limb WMSDs, whereas autonomy over work breaks was associated with lower odds. The detailed region-specific results are listed in Supplementary Table S3 (available at <https://weekly.chinacdc.cn/>).

DISCUSSION

This study found that civil aviation flight attendants had a prevalence of WMSDs, particularly in the neck, shoulders, and lower back, higher than that in both the National Occupational Group and the Comparable Industry Subgroup. Conversely, elbow and hand/wrist WMSDs were less common among flight attendants than among comparison workers. This distinct

anatomical distribution suggests that WMSDs among flight attendants may be related to cabin-specific ergonomic and work-organization exposures, rather than reflecting a uniform increase across all body regions.

A key finding of the generalized linear mixed model was that flight attendant occupation was no longer significantly associated with WMSDs after adjusting for demographic, ergonomic, and work-organization factors when compared with the Comparable Industry Subgroup. This finding highlights the importance of ergonomics and work-organization exposures in interpreting the higher prevalence among flight attendants, who reported higher frequencies of working in uncomfortable postures, repetitive truncal

movements, prolonged static neck postures, extended daily working hours, and insufficient rest. All of these factors were independently associated with WMSDs and may serve as prevention targets. Region-specific models among flight attendants showed similar patterns, further supporting prevention efforts that consider both cabin-related postural demands and work-organization measures, including adequate staffing, optimized scheduling, and protected rest opportunities.

The findings in this study are subject to at least three limitations. First, because of its cross-sectional design, causal relationships between occupational exposures and WMSDs could not be established. Second, both WMSDs and occupational exposures were assessed using self-reported questionnaire data, which may have introduced recall and reporting bias. Differential symptom awareness across occupational groups cannot be excluded. Third, although the Comparable Industry Subgroup showed improved comparability in terms of sex distribution and physical workload, residual confounding may have remained because occupation-specific factors, such as cabin environmental conditions, circadian disruption, and psychosocial demands, were not measured.

This study suggests several practical options for preventing WMSDs among flight attendants. Routine occupational health surveillance may help to identify high-prevalence groups and monitor trends. Cabin ergonomic improvements aimed at reducing awkward trunk and neck postures can be combined with administrative measures, including adequate staffing, sufficient rest between flights, and greater autonomy over work breaks. Ergonomic training and targeted exercise programs may provide additional support when integrated into broader preventive efforts.

Conflicts of interest: No conflicts of interest.

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Ethical statement: The Medical Ethics Review Committee of the National Institute of Occupational Health and Poison Control, Chinese Center for Disease Control and Prevention, approved this study (Approval No.: NIOHP202122). All participants provided informed consent.

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SUPPLEMENTARY MATERIAL

SUPPLEMENTARY TABLE S1. Prevalence of WMSDs by body region among flight attendants and comparison groups, China, 2018–2023.

Body regions	Flight attendants (n=1,341)			National occupational group (n=87,268)			Comparable industry subgroup (n=16,224)		
	Number	Actual prevalence rate (%)	Standardized prevalence rate (%)	Number	Actual prevalence rate (%)	Standardized prevalence rate (%)	Number	Actual prevalence rate (%)	Standardized prevalence rate (%)
Neck	494	36.84	36.65	19,341	22.16	21.64***	5,134	31.64	31.08***
Shoulders	382	28.49	31.33	16,153	18.51	18.20***	4,166	25.67	25.46*
Upper Back	202	15.06	19.36	11,213	12.85	12.49*	2,673	16.48	16.28
Lower Back	273	20.36	20.83	12,921	14.81	14.68*	3,038	18.73	18.49
Elbows	52	3.88	4.78	5,922	6.79	6.91***	1,123	6.92	7.15***
Hands/Wrists	93	6.94	6.39	10,345	11.85	11.73**	2,168	13.36	13.76***
Buttocks/Thighs	119	8.87	10.18	8,324	9.54	9.49	1,926	11.87	11.55**
Knees	140	10.44	13.47	8,465	9.70	9.77	1,678	10.34	10.50
Feet/Ankles	153	11.41	11.84	10,256	11.75	11.04	2,908	17.92	17.05***
Any Region	684	51.01	51.47	32,563	37.31	36.66***	7,376	45.46	44.57***

Note: Standardized prevalence rate based on the age distribution of the 18–60 year age group in China's seventh national population census.

Abbreviation: WMSDs=work-related musculoskeletal disorders.

* $P<0.05$, ** $P<0.01$, *** $P<0.001$, compared with the flight attendant group (reference).

SUPPLEMENTARY TABLE S2. Working posture characteristics among flight attendants and comparison groups, China, 2018–2023.

Variable	Flight attendants (n=1,341) (%)	National occupational group (n=87,268) (%)	Comparable industry subgroup (n=16,224) (%)
Back posture at work			
Upright	440 (32.81)	30,397 (34.83)	4,811 (29.65)***
Slight bend	731 (54.51)	46,241 (52.99)	9,695 (59.76)
Significant bend	170 (12.68)	10,630 (12.18)	1,718 (10.59)
Frequent bending with twisting			
Yes	760 (56.67)	36,081 (41.35)***	6,076 (37.45)***
No	581 (43.33)	51,187 (58.65)	10,148 (62.55)
Repetitive trunk/waist/back movements			
Yes	964 (71.89)	43,639 (50.01)***	8,416 (51.87)***
No	377 (28.11)	43,629 (49.99)	7,808 (48.13)
Prolonged bent posture			
Yes	605 (45.12)	23,925 (27.42)***	5,045 (31.10)***
No	736 (54.88)	63,343 (72.58)	11,179 (68.90)
Neck posture at work			
Upright	226 (16.85)	16,372 (18.76)*	2,235 (13.78)**
Slightly forward	733 (54.66)	46,491 (53.27)	9,208 (56.76)
Significantly forward	363 (27.07)	22,169 (25.40)	4,654 (28.69)
Tilted back	19 (1.42)	2,236 (2.56)	127 (0.78)
Prolonged head-down posture			
Yes	720 (53.69)	41,174 (47.18)***	10,195 (62.84)***
No	621 (46.31)	46,094 (52.82)	6,029 (37.16)
Wrist edge contact			
Yes	533 (39.75)	29,538 (33.85)***	5,283 (32.57)***
No	808 (60.25)	57,730 (66.15)	10,941 (67.44)
Hand pinching/clutching tasks			
Yes	1,014 (75.62)	66,779 (76.52)	12,220 (75.32)
No	327 (24.38)	20,489 (23.48)	4,004 (24.68)
Ability to change leg posture			
Yes	793 (59.13)	67,785 (77.67)***	11,826 (72.89)***
No	548 (40.87)	19,483 (22.33)	4,398 (27.11)
Prolonged knee-bent posture			
Yes	578 (43.10)	27,138 (31.10)***	6,074 (37.44)***
No	763 (56.90)	60,130 (68.90)	10,150 (62.56)
Repetitive lower limb/ankle movements			
Yes	807 (60.18)	33,700 (38.62)***	6,304 (38.86)***
No	534 (39.82)	53,568 (61.38)	9,920 (61.14)

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ compared with the flight attendant group (reference).

SUPPLEMENTARY TABLE S3. Factors associated with region-specific work-related musculoskeletal disorders among flight attendants in multivariable logistic regression analyses, China, 2018–2023.

Body region	Variable	Coefficient	Wald χ^2	OR (95% CI)	P
Neck	Gender				
	Men	–	–	1.00	–
	Women	0.837	22.84	2.31 (1.64, 3.26)	<0.001
	Service duration (years)				
	<5	–	–	1.00	–
	25–29	–0.881	4.53	0.42 (0.18, 0.93)	0.033
	Working in uncomfortable postures				
	Rarely/never	–	–	1.00	–
	Sometimes	0.650	10.36	1.92 (1.29, 2.85)	0.001
	Often	1.070	23.94	2.92 (1.90, 4.47)	<0.001
	Very frequently	1.171	22.72	3.23 (1.99, 5.22)	<0.001
	Number of working hours per day				
	≤8	–	–	1.00	–
	>8	0.390	8.07	1.48 (1.13, 1.93)	0.005
	Sufficient rest time				
	No	–	–	1.00	–
	Yes	–0.573	10.97	0.56 (0.40, 0.79)	0.001
Trunk (lower back, upper back)	Autonomy over work breaks				
	No	–	–	1.00	–
	Yes	–0.855	4.22	0.43 (0.19, 0.96)	0.040
	Department understaffing				
	No	–	–	1.00	–
	Yes	0.349	6.18	1.42 (1.08, 1.87)	0.013
	Gender				
	Men	–	–	1.00	–
	Women	0.641	8.55	1.90 (1.24, 2.92)	0.003
	Working in uncomfortable postures				
	Rarely/never	–	–	1.00	–
	Often	0.689	6.31	1.99 (1.16, 3.41)	0.012
	Very frequently	0.787	6.96	2.20 (1.22, 3.95)	0.008
	Number of working hours per day				
	≤8	–	–	1.00	–
	>8	0.531	10.25	1.70 (1.23, 2.35)	0.001
	Sufficient rest time				
	No	–	–	1.00	–
	Yes	–0.720	9.76	0.49 (0.31, 0.77)	0.002
Upper limbs (shoulders, hands/wrists, elbows)	Gender				
	Men	–	–	1.00	–
	Women	1.290	38.86	3.63 (2.42, 5.45)	<0.001
	Marital status				
	Unmarried	–	–	1.00	–
	Living alone	–1.237	4.74	0.29 (0.10, 0.88)	0.030

Continued

Body region	Variable	Coefficient	Wald χ^2	OR (95% CI)	P
Upper limbs (shoulders, hands/wrists, elbows)	Working in uncomfortable postures				
	Rarely/never	–	–	1.00	–
	Sometimes	0.482	5.21	1.62 (1.07, 2.45)	0.022
	Often	0.956	18.03	2.60 (1.67, 4.05)	<0.001
	Very frequently	0.952	14.09	2.59 (1.58, 4.26)	<0.001
	Number of working hours per day				
	≤8	–	–	1.00	–
	>8	0.495	11.75	1.64 (1.24, 2.18)	0.001
	Autonomy over work breaks				
	No	–	–	1.00	–
	Yes	–1.296	6.98	0.27 (0.11, 0.72)	0.008
	Department understaffing				
	No	–	–	1.00	–
	Yes	0.386	7.21	1.47 (1.11, 1.95)	0.007
	Wrist placement on hard edges				
	No	–	–	1.00	–
	Yes	0.267	4.07	1.31 (1.01, 1.69)	0.044

Note: All factors listed in the table were statistically significant ($P<0.05$).

Methods and Applications

Targeted Cycloplegia in Refractive Screening of Children and Adolescents: Development and Internal Validation of a Pre-Cycloplegia Risk Prediction Model — 10 PLADs, China, 2020–2024

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ABSTRACT

Introduction: Cycloplegic refraction is the gold standard for accurate refractive assessment in children and adolescents, but its use is limited by operational complexity and low acceptance. Because effective tools for identifying individuals who require cycloplegia are lacking, this study aimed to develop a risk prediction model for refractive misclassification based on pre-cycloplegia parameters to assist targeted cycloplegic refraction.

Methods: A total of 43,760 children and adolescents aged 5–18 years were enrolled from 10 provincial-level administrative divisions in China using stratified cluster probability-proportional-to-size (PPS) sampling. Pre-cycloplegia data, including individual characteristics, ocular indicators, and lifestyle factors, were collected. Binary logistic regression was used to develop the model, and receiver operating characteristic (ROC) curves were used to determine the optimal cutoff value.

Results: The final model included six core variables and achieved an overall classification accuracy of 79.4% and an area under the ROC curve (AUC) of 0.730. The optimal cutoff score was 18.4. Moderate or low uncorrected visual acuity and abnormal axial length were major risk factors, whereas a higher school stage was protective.

Conclusion: The prediction model demonstrated favorable performance and identified individuals at high risk of refractive misclassification. Individuals with a risk score ≥ 18.4 may be prioritized for cycloplegic refraction.

accurate refractive screening crucial for myopia prevention and control (1). Cycloplegic refraction, which eliminates pseudomyopia by paralyzing accommodation, is regarded as the clinical gold standard (2). Nevertheless, its large-scale application is limited by procedural complexity, potential adverse effects, long examination duration, and low acceptance among children and caregivers. Consequently, non-cycloplegic screening is widely used in large-scale screening programs but carries a high risk of refractive misclassification.

Currently, no evidence-based tool exists to stratify populations into high-risk individuals needing cycloplegia and low-risk individuals for whom non-cycloplegic screening is adequate. This creates a dilemma: overuse of cycloplegia increases the procedural burden, while underuse reduces accuracy. Most existing studies have focused on confirming the advantages of cycloplegia, whereas few have attempted to identify candidates for cycloplegia using pre-cycloplegia indicators (3).

To fill this gap, we developed a risk prediction model for refractive misclassification using pre-cycloplegia individual, ocular, and lifestyle data from a large multicenter sample of children and adolescents. The model aims to determine key risk factors, establish an optimal cutoff score, and provide a practical tool for personalized screening. This strategy balances accuracy and feasibility and supports more efficient refractive screening in clinical and public health practice.

METHODS

This cross-sectional study enrolled 43,760 participants aged 5–18 years from November 2020 to July 2024. Stratified cluster probability-proportional-to-size (PPS) sampling was applied across 10 provincial-level administrative divisions in eastern

Refractive errors are a leading cause of visual impairment in children and adolescents, making

China (Beijing, Zhejiang, Guangdong, and Shandong), central China (Henan, Hunan, and Shanxi), western China (Shaanxi and Chongqing), and northeastern China (Liaoning) to ensure geographic and economic representativeness. Sample regions were selected according to per capita gross domestic product (GDP), and schools and classes were selected proportionally, covering primary, junior, and senior high school students. All students in the selected classes were included in this study. Participants with ineligible refractive data, invalid results because of noncooperation, or incomplete cycloplegic refraction data were excluded. Missing data were handled using complete case analysis. For analyses not involving axial length, the full sample of 43,760 was used; for analyses including axial length as a variable, 43,539 participants with complete axial length records were analyzed. Given the very low missing rate (0.50%) and random distribution of missing cases, no data imputation was performed.

The following pre-cycloplegia data were collected to inform screening decisions. Individual characteristics included sex, school stage (primary, junior high, or senior high school), and economic level (high, middle, or low, classified by regional per capita GDP). Ocular indicators included uncorrected visual acuity [UA, stratified as low (4.0–4.5), moderate (4.6–4.9), or good (5.0–5.2)], axial length (normal or abnormal), and intraocular pressure (normal or abnormal). Lifestyle factors included electronic device use (≤ 1 h/d or > 1 h/d), outdoor activity (< 2 h/d or ≥ 2 h/d), and sleep duration (adequate or inadequate).

All students received four applications of 0.5% tropicamide with one drop administered at 5-min intervals. Cycloplegic refraction was measured three times in each eye using a desktop autorefractor (KR-800; Topcon, Tokyo, Japan), and the mean of the three measurements was used as the refractive value. The adequacy of cycloplegia and pupillary dilation was assessed 30 min after the final application. Right-eye data were used for all statistical analyses. A correct classification was defined as agreement between noncycloplegic and cycloplegic refraction (i.e., both methods classified the participants as myopic or both classified the participants as nonmyopic). Discordant results (false-positive or false-negative classifications) were defined as refractive misclassification. Participants with discordant results were classified as requiring cycloplegia. Standardized protocols and strict multilevel quality-assurance procedures were implemented across all 10 provincial sites throughout

the study period. All autorefractors underwent quarterly calibration and annual intersite consistency testing to control measurement bias. On-site medical and school health staff completed standardized training and competency assessments before data collection, and standardized cycloplegia procedures were enforced uniformly. A three-tier quality control mechanism, including real-time data verification, daily random sample review, and annual cross-site inspection, was adopted to ensure data consistency and reliability. Statistical analyses were conducted using R software (version 4.5.2, R Foundation for Statistical Computing, Vienna, Austria). Continuous variables were expressed as the mean $\pm$ standard deviation (SD) and compared using *t* tests, one-way analysis of variance (ANOVA), or Welch's ANOVA for unequal variances. Categorical variables were reported as frequencies (percentages) and analyzed by the χ^2 test. Forward stepwise binary logistic regression was used to identify independent factors associated with refractive misclassification. Model performance was assessed using receiver operating characteristic (ROC) curves, including the area under the curve (AUC), sensitivity, specificity, and the Youden index; the latter was used to determine the optimal cutoff. A risk-scoring system was established based on standardized regression coefficients. A two-sided $P < 0.05$ was considered statistically significant.

Internal validation was conducted using a random hold-out strategy. The full sample was randomly divided into a training set (70%) for model construction and a test set (30%) for independent performance verification.

Subgroup analyses were conducted to assess model generalizability across geographic regions (eastern, central, western, and northeastern China) and economic strata (high, middle, and low). AUC, sensitivity, specificity, and optimal cutoff were calculated for each subgroup. A sensitivity analysis was conducted by randomly excluding 10% of participants to assess the robustness of the main findings.

RESULTS

Sex, school stage, UA category, axial length, economic level, electronic device use, outdoor activity time, and sleep duration were significantly associated with refractive misclassification (all $P < 0.05$), whereas intraocular pressure was not ($P = 0.363$). Misclassification rates were highest in the moderate UA group (45.0%, 6,460/14,355) and the low UA group

(44.8%, 2,329/5,199) and were substantially higher in the abnormal axial length group (45.8%, 2,250/4,931) than in the normal axial length group (22.2%, 8,587/38,626) (Table 1).

Forward stepwise logistic regression retained six predictors in the final model: school stage, UA category, axial length classification, economic level, electronic device use, and sleep duration (Table 2). The model achieved an overall classification accuracy

of 79.4%, with Cox–Snell $R^2=0.270$ and Nagelkerke $R^2=0.371$.

In subgroup analyses by geographic region, the AUC was 0.752 [95% confidence interval (CI): 0.744, 0.760] in eastern China, 0.728 (95% CI: 0.720, 0.736) in central China, 0.695 (95% CI: 0.678, 0.712) in western China, and 0.639 (95% CI: 0.614, 0.664) in northeastern China. The optimal cutoff scores ranged from 18.2 to 18.6 points across the four regions. When

TABLE 1. Univariate analysis of refractive misclassification among children and adolescents aged 5–18 years in 10 PLADs, China, 2020–2024.

Influencing factor	Sample size	Test statistic	P
Sex			
Male	22,530	Welch's F =38.657	<0.001
Female	21,230		
School stage			
Primary	41,190	Welch's F =839.285	<0.001
Junior	1,585		
Senior	985		
Uncorrected visual acuity			
Low (4.0–4.5)	5,199	Welch's F =8,244.978	<0.001
Moderate (4.6–4.9)	14,355		
Good (5.0–5.2)	24,206		
Axial length			
Normal	38,626	Welch's F =1,133.819	<0.001
Abnormal	4,913		
Economic level			
High	14,417	Welch's F =160.707	<0.001
Middle	22,712		
Low	6,631		
Intraocular pressure			
Normal	40,325	F(ANOVA) =0.829	0.363
Abnormal	3,435		
Electronic device usage			
≤1 h/d	16,090	Welch's F =21.020	<0.001
>1 h/d	27,670		
Outdoor activity time			
<2 h/d	20,739	Welch's F =7.851	<0.001
≥2 h/d	23,021		
Sleep duration			
Adequate	7,946	Welch's F =52.298	<0.001
Inadequate	35,814		

Note: Post hoc comparisons using the LSD test were performed for variables with more than two subgroups. School stage: Primary vs. Junior, $P<0.001$; Primary vs. Senior, $P<0.001$; Junior vs. Senior, $P=0.102$. For uncorrected visual acuity, all pairwise comparisons were $P<0.001$. For economic level, all pairwise comparisons had $P<0.001$.

Abbreviation: LSD=least significant difference; ANOVA=one-way analysis of variance.

TABLE 2. Binary logistic regression analysis of refractive misclassification among children and adolescents.

Variable	B value	Standard error	Wald χ^2	P	OR (95% CI)
School stage	-0.837	0.056	222.44	<0.001	0.43 (0.39, 0.48)
Uncorrected visual acuity (Ref: Good)			9,451.59	<0.001	
Low	1.121	0.070	259.60	<0.001	3.07 (2.68, 3.52)
Moderate	3.459	0.070	2,461.17	<0.001	31.79 (27.73, 36.45)
Axial length (Ref: Normal)	1.314	0.050	682.36	<0.001	3.72 (3.37, 4.11)
Economic level (Ref: Low)			136.58	<0.001	
High	0.135	0.038	12.35	<0.001	1.14 (1.06, 1.23)
Middle	-0.172	0.037	22.15	<0.001	0.84 (0.78, 0.90)
Electronic device usage (Ref: ≤ 1 h/d)	0.049	0.025	3.87	0.049	1.05 (1.00, 1.10)
Sleep duration (Ref: Adequate)	0.133	0.031	18.82	<0.001	1.14 (1.08, 1.21)
Constant	-2.843	0.108	694.77	<0.001	0.06

Abbreviation: OR=odds ratio; CI=confidence interval; SE=standard error; Ref=reference category; Wald χ^2 =Wald chi-square test statistic; B=unstandardized regression coefficient.

stratified by economic level, the AUC was 0.774 (95% CI: 0.766, 0.782) in regions with a high economic level, 0.721 (95% CI: 0.714, 0.729) in regions with a middle economic level, and 0.578 (95% CI: 0.562, 0.594) in regions with a low economic level; the corresponding specificities were 90%, 84%, and 85%, respectively.

After 10% of the participants were randomly excluded in the sensitivity analysis, the model yielded an AUC of 0.729 (95% CI: 0.723, 0.734), with an optimal cutoff of 18.4 points. All six core variables remained in the final model, and the odds ratio (OR) estimates for the key predictors changed by less than 3% relative to those in the primary analysis, indicating that the estimates were not materially altered in this sensitivity analysis.

In the hold-out internal validation, the model achieved an AUC of 0.733 (95% CI: 0.727–0.740) in the training set and 0.721 (95% CI: 0.711–0.731) in the test set. The high consistency of discriminative performance, core predictors and cutoff value between the two sets demonstrated good stability of the model with no obvious overfitting.

A risk-scoring system was constructed using standardized regression coefficients (Table 3). Total risk score=School Stage score + Uncorrected Visual Acuity score + Axial Length score + Economic Level score + Sleep Duration score + Electronic Device Usage score. ROC analysis yielded an AUC of 0.730 (95% CI: 0.725, 0.735; $P<0.001$). At the optimal cutoff of 18.4 points, the Youden index was 0.509, sensitivity was 64.6%, and specificity was 86.3%. This cutoff was used to classify participants as being at high or low risk of refractive misclassification.

DISCUSSION

Using data from 43,760 participants, this study developed a six-variable prediction model for refractive misclassification in children and adolescents, with an AUC of 0.730 and a specificity of 86.3%. This model may help clinicians and public health practitioners identify individuals at high risk of misclassification and support the targeted use of cycloplegic refraction.

Being at a higher school stage was a protective factor (OR=0.43), possibly because older adolescents have more stable refractive status and accommodative function and may cooperate better during examinations (4–5). UA category had the strongest association with misclassification: compared with the good UA group (5.0–5.2), the moderate UA group (4.6–4.9) had 31.79-fold higher odds of misclassification, whereas the low UA group had 3.07-fold higher odds. The elevated predicted risk among primary school children supports consideration of targeted cycloplegia in this age group. Clinically, moderate UA often reflects mild myopia or "pseudomyopia," in which active accommodation under noncycloplegic conditions distorts measurements, making this group prone to false-positive or false-negative classification and therefore an important target for cycloplegic refraction (6). In contrast, the good UA group primarily included emmetropic or mildly hyperopic children and adolescents with stable accommodation, resulting in the lowest misclassification rate and more reliable noncycloplegic screening. Abnormal axial length (OR=3.72) was another important predictor. As an objective ocular measurement associated with myopia

TABLE 3. Risk-score assignments for refractive misclassification in children and adolescents.

Variable	Coded value	Standardized B value	Score
School stage			
Primary	1	-6.29	-6.29
Junior	2	-6.29	-12.58
Senior	3	-6.29	-18.87
Uncorrected visual acuity			
Good	1	0	0
Moderate	2	26.01	26.01
Low	3	8.43	8.43
Axial length			
Normal	1	9.88	0
Abnormal	2	9.88	9.88
Economic level			
Low	1	-1.29	0
Middle	2	-1.29	-1.29
High	3	1.02	1.02
Electronic device usage			
≤1 h/d	1	0.37	0
>1 h/d	2	0.37	0.37
Sleep duration			
Adequate	1	1.00	0
Inadequate	2	1.00	1.00

Abbreviation: B=unstandardized regression coefficient; SE=standard error.

and its progression, axial length may provide useful complementary information during pediatric refractive screening (7). The association between economic level and misclassification was not monotonic: relative to regions with a low economic level, the odds were higher in regions with a high economic level but lower in regions with a middle economic level. Therefore, this finding cannot be explained solely by differences in vision-monitoring systems or awareness and requires further investigation (8). Electronic device use for >1 h/d showed a small association with refractive misclassification ($OR=1.05$). Although electronic device use has been associated with myopia, the mechanism underlying its association with refractive misclassification requires further study (9). Inadequate sleep was also associated with refractive misclassification; however, the mechanism underlying this association requires further study (10). Therefore, a comprehensive assessment of vision-monitoring systems is required to enhance the accuracy and continuity of refractive surveillance in children and adolescents. Although cycloplegia is the gold standard for refractive assessment of children and adolescents, its

complexity restricts its widespread use. This study provides a potentially practical tool to identify candidates who may require cycloplegia, rather than merely verifying its value. From a national public health perspective, this risk-scoring system could potentially be incorporated into routine annual vision screening managed by local CDCs. During school-based screening, school physicians and primary eye care personnel could use the required data to calculate each student's risk score, provided that axial-length measurements are available. The 18.4-point cutoff may support clinical decision-making. Individuals scoring ≥ 18.4 may be prioritized for cycloplegic refraction, especially primary school students with moderate or low UA or abnormal axial length. However, the sensitivity of 64.6% indicates that 35.4% of individuals with refractive misclassification would not be identified at this threshold. Therefore, a score <18.4 should not be used alone to conclude that noncycloplegic screening is sufficiently reliable avoiding unnecessary procedures, lowering workload, reducing discomfort. If prospectively validated, this tiered approach may help allocate limited ophthalmic

personnel, cycloplegic agents, and equipment more efficiently. Reducing unnecessary cycloplegic examinations may also decrease discomfort, including photophobia, blurred near vision, and ocular irritation, and may improve screening adherence. For CDC administrators, the standardized quantitative score may guide targeted resource allocation toward high-risk subgroups, particularly primary school students with poor vision or abnormal axial length, potentially supporting more equitable and efficient myopia-control efforts.

Subgroup analyses showed that the optimal cutoff values were relatively consistent across geographic and economic strata. However, discriminatory performance varied substantially, with AUCs ranging from 0.639 to 0.752 across geographic regions and from 0.578 to 0.774 across economic strata. The sensitivity analysis produced results similar to those of the primary analysis. However, the relatively low AUCs in northeastern China and regions with a low economic level indicate that the model may not perform equally well in all populations. Independent external validation and possible subgroup-specific refinement are therefore needed before nationwide implementation.

This study had several limitations. First, its cross-sectional design precludes causal inference. Future prospective studies are needed to validate the model's long-term predictive performance in children and adolescents. Second, pre-cycloplegia factors such as corneal curvature and accommodative amplitude were not included, which may have limited the accuracy of the model. Third, economic level was defined according to regional GDP rather than individual household economic status. Fourth, the model's discriminatory performance varied substantially across geographic and economic subgroups. Finally, the sensitivity of 64.6% indicates that the selected cutoff would fail to identify some individuals with refractive misclassification. Despite these limitations, the model's relatively high specificity suggests that it may help reduce unnecessary cycloplegia among appropriately identified low-risk individuals; however, it does not ensure that all high-risk individuals will be identified.

In conclusion, this study developed a risk-scoring system for refractive misclassification in children and adolescents. A score ≥ 18.4 may help prioritize individuals for cycloplegic refraction; however, scores < 18.4 should be interpreted together with other clinical information because the model's sensitivity was 64.6%. The model may help prioritize cycloplegic-refraction resources for high-risk groups, including

primary school children, children with UA of 4.6–4.9, and those with abnormal axial length. However, external validation and possible refinement in lower-performing subgroups are required before nationwide implementation. If validated, this approach could balance accuracy and practicality and provide an evidence-based tool for optimizing refractive screening in children and adolescents.

Conflicts of interest: No conflicts of interest.

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Commentary

Beyond Soil Selenium: Agroindustrial Exposure Pathways and Diabetes Risk Assessment in Contemporary China

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ABSTRACT

A recent multicenter Chinese cohort study reported a prospective association between high serum selenium (Se) status and incident type 2 diabetes (T2D), while interpreting regional serum Se variation largely through local soil geochemistry. Although the correlation between soil and serum Se is robust at the regional scale, the inferential leap from geochemistry to dietary exposure may underestimate contemporary food system inputs. Two structural features of modern China, institutionalized Se supplementation in compound feed since 2009 and large-scale importation of soybean meal from geochemically heterogeneous origins, have introduced agroindustrial Se pathways that may partially decouple animal-source dietary Se from local soils. Risk mapping based solely on geochemical proxies may misclassify exposure burden in regions where these pathways dominate. Future Se exposure assessments should integrate geochemical, dietary, food supply chain, environmental, and biomarker data, particularly for populations with serum Se levels comparable to the highest tertile in that cohort.

Given the country's heterogeneous soil chemistry and rapidly evolving food system, the question of whether environmental geography shapes the burden of metabolic diseases in China is of mounting public health importance. Wang et al. (1) reported that residents in the highest serum Se tertile (107.2–162.8 µg/L) face a 35% greater risk of incident T2D, with a stronger association in men (relative risk=1.96), in a prospective multicenter Chinese cohort in which exposure was characterized through serum Se as an internal-dose biomarker rather than dietary recall alone. This design substantially strengthens exposure characterization and supports the prospective interpretation of the Se–T2D association in a Chinese

population.

However, one interpretive step warrants reconsideration, namely, the attribution of regional serum Se variation to local soil geochemistry. The authors' own stepwise model retained three predictors, that is, soil Se, aquatic product consumption, and PM_{2.5}, which together accounted for 82% of the regional variance in mean serum Se. Soil Se alone explained 67% of the variance. The retention of aquatic product consumption and PM_{2.5}, along with soil Se, indicated that non-soil predictors added explanatory information at the city level. However, this ecological model could not identify the specific exposure pathways involved. The simplification to a soil-Se-only prediction model was adopted explicitly for interpretability and applicability outside China, a transparent and pragmatic modeling choice. However, this methodological convenience should not be interpreted as evidence that local soil Se is the primary determinant of serum Se levels in contemporary China. The authors note that actual serum Se "may deviate in areas with substantial non-local food sourcing, high seafood intake, Se-fortified products or feed supplementation." These caveats likely capture the important determinants of dietary Se exposure in many regions of contemporary China, rather than marginal exceptions.

The two structural features of China's modern food system complicate the importance of local soil geochemistry as a governing exposure pathway (Figure 1). Since the promulgation of China's Regulation on the Safe Use of Feed Additives in 2009 (2), selenium supplementation in compound feed and total mixed rations has been institutionalized under mandatory maximum inclusion limits. In the extensive Se-deficient zones of China, which encompass more than half of the country's land area (3), locally produced feed ingredients are similarly constrained by low environmental Se availability. This makes livestock Se requirements unattainable from local crops alone. Therefore, routine Se supplementation of poultry and swine diets, increasingly with organic sources such as



FIGURE 1. Multi-source selenium exposure pathways in contemporary China.

Note: Imported soybean meal and regulated selenium feed additives, including selenium yeast, sodium selenite, and nano-selenium, enter compound animal feed and reach consumers through animal-source foods. Seafood and locally produced plant foods, including those from localized high-selenium areas, such as Ziyang and Enshi, provide additional dietary sources. These pathways shape human selenium status. Here, higher serum selenium was prospectively associated with incident type 2 diabetes risk.

Abbreviation: Se=selenium; T2D=type 2 diabetes.

selenized yeast, has become standard industry practice. The resulting feed-to-food Se transfer partially decouples animal-source dietary Se from a local geochemical background. This means that residents of historically low-Se regions may obtain substantially more Se through animal-source foods than that predicted by soil maps. China's soybean meal supply chain, the primary protein source in compound feed, is heavily dependent on imports, approaching 100 million metric tons annually (4). It is sourced predominantly from Brazil, the United States, and Argentina. Given the pronounced geochemical heterogeneity among these major exporting regions, where US Midwest soils are among the most Se-replete globally, in contrast to the lower Se agricultural zones of Brazil and China (5), Se concentrations in imported soybean meal are likely to vary substantially by origin. This introduces a supply chain Se input that cannot be inferred from domestic soil maps alone. The soil-serum Se correlation reported by Wang et al. ($r=0.83$ at the city scale) is undeniably robust. However, the ecological model on which it rests was not constructed to distinguish geochemical from

agroindustrial exposure pathways, and the spatial signal it captures likely reflects both. These feed chain inputs may not be captured by local soil maps alone and should be assessed through measurements of feed, animal-source foods, and human biomarkers.

These considerations do not challenge the biological reality or public health significance of the Se-T2D association itself. Independent human evidence supports this association: selenium supplementation increased incident T2D in a large randomized trial (6). Higher serum Se has been positively associated with diabetes prevalence and with elevated fasting glucose and HbA1c in nationally representative US adults (7). In Chinese populations, the highest Se quartile in nail and serum measurements predicted a greater risk of incident diabetes and pre-diabetes (8). At the mechanistic level, selenoprotein overabundance, whether through GPX1 overexpression driving obesity and insulin resistance (9), or through the hepatokine action of selenoprotein P suppressing AMP-activated protein kinase signaling (10), impairs glucose homeostasis in experimental models. Another pathway, centered on the *de novo* serine synthesis pathway (SSP)

in high-Se mice, has been characterized, in which upregulation of phosphoglycerate dehydrogenase (PHGDH) is accompanied by impaired glucose and insulin tolerance (11). In selenomethionine-treated myotubes, SSP activation coincides with the suppression of PI3K–AKT–mTOR insulin signaling (12). Both pharmacological PHGDH inhibition and exogenous serine supplementation attenuate high-Se-induced insulin resistance in vivo (13), establishing the causal directionality and reversibility of this axis. These mechanistically distinct routes, selenoprotein-mediated redox dysregulation, and SSP-driven metabolic remodeling, have been reviewed comprehensively elsewhere (14) and lend robust biological support to the prospective risk signal reported by Wang et al. This pronounced male-specific risk pattern is consistent with the evidence that estrogen-mediated regulation of selenoprotein expression may buffer women against Se-related metabolic perturbation (15).

The most significant contribution by Wang et al. may be the identification of a clinically relevant high-serum Se phenotype that is prospectively associated with T2D risk. In contemporary China, this phenotype is likely shaped by the intersection of local geochemistry, institutionalized feed chain Se supplementation, and globalized agricultural commodity flows. Treating it as a purely geochemical signal misclassifies the exposure burden in regions where agroindustrial Se inputs are substantial. Meanwhile, selenium is an essential micronutrient, and its deficiency remains a concern in historically low-Se regions. Therefore, the prevention of deficiency and avoidance of excessive exposure are complementary rather than competing public health objectives. Future risk mapping should integrate multi-source exposure data spanning soil and water, crops, food circulation, feed supplementation, nutritional fortification, atmospheric co-exposures, and individual dietary patterns with internal-dose biomarkers rather than relying on geochemical proxies alone. Targeted and monitored Se interventions may be appropriate for Se-deficient populations, whereas routine additional enrichment should be avoided in Se-replete populations. Populations with a high internal Se status may require source tracing and continued biomarker surveillance. In populations with high serum Se levels, caution regarding further Se enrichment is warranted, regardless of the upstream source. Understanding where high-Se phenotypes arise and through which pathways is the next step toward geographically nuanced and effective prevention.

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