

Association of respiratory muscle strength with pre-frailty and overall functional status in community-dwelling Japanese older adults: a cross-sectional study

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Abstract

Background Physical frailty is marked by diminished physiological reserve and increased vulnerability. Pre-frailty, an intermediate state, is prevalent among community-dwelling older adults and linked to functional decline. This study examined the association between respiratory muscle strength and pre-frailty (primary outcome) and overall functional status (secondary outcome) in community-dwelling older adults in Japan.

Methods In this cross-sectional study, 324 adults aged ≥ 65 years participated in a community health survey in Fukushima Prefecture (August 2024–February 2025). Respiratory muscle strength was measured using maximal inspiratory pressure (MIP) and maximal expiratory pressure (MEP). Frailty status was assessed with the revised Japanese Cardiovascular Health Study criteria. Participants classified as frail (score 3–5) were excluded, leaving 313 individuals for analysis, comparing pre-frailty (score 1–2) with robustness (score 0). Functional status was evaluated using the Kihon Checklist (KCL), grip strength, knee extension strength, walking speed, and skeletal muscle index (SMI). Multivariable logistic regression models were constructed separately for MIP and MEP, adjusting for age, sex, body mass index, smoking status, and respiratory disease history.

Results Lower MIP ($p < 0.001$) and MEP ($p = 0.002$) were significantly associated with greater odds of pre-frailty in both crude and covariate-adjusted models. In secondary analyses of overall functional status, lower MIP was significantly associated with higher KCL scores and lower grip strength, knee extension strength, walking speed, and SMI. Moreover, lower MEP was significantly associated with higher KCL scores and lower grip strength, knee extension strength, and walking speed, whereas its association with SMI was not significant after adjustment. Receiver operating characteristic analyses showed only modest discriminatory ability for identifying pre-frailty.

Conclusion Respiratory muscle strength is associated with pre-frailty and overall functional status in community-dwelling older adults and may be one of several factors associated with early vulnerability.

Clinical trial number Not applicable.

Keywords Respiratory muscle strength · Maximal inspiratory pressure · Maximal expiratory pressure · Pre-frailty · Functional status · Community-dwelling older adults

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Background

Frailty is a clinical syndrome characterized by age-related declines in physiological reserve and multisystem function, resulting in increased vulnerability to stressors [1]. Numerous studies have demonstrated that physical frailty is associated with falls, hospitalization, disability, and mortality [1–5]. Therefore, identifying modifiable determinants and implementing early interventions are essential to prevent functional decline in older adults.

Frailty is increasingly recognized as a dynamic process, particularly at its intermediate stage, pre-frailty. In the widely used Fried phenotype, pre-frailty is defined by the presence of one or two frailty components and represents a transitional state between robustness and frailty [5]. This stage is clinically important because it confers an elevated risk of progression while remaining potentially reversible, making it a pragmatic target for preventive strategies.

Although physical frailty and sarcopenia are overlapping constructs, they are not interchangeable. Sarcopenia primarily reflects impaired muscle health, whereas physical frailty represents a broader state of vulnerability encompassing weakness, slowness, exhaustion, low physical activity, and weight loss. These functionally oriented components are closely associated with mobility, activities of daily living (ADL), and functional independence [5, 6]. Thus, physical pre-frailty may capture early vulnerability extending beyond impaired skeletal muscle function alone. From a community health perspective, identifying factors associated with physical pre-frailty may inform preventive strategies aimed at delaying or preventing subsequent functional decline.

Respiratory muscle strength may represent a physiologically relevant correlate of this early vulnerability. Reduced respiratory muscle strength may be associated with greater exertional dyspnea, reduced exercise tolerance, and lower physical activity, all of which are relevant to the physical frailty phenotype. Because physical frailty reflects multisystem vulnerability, factors beyond limb skeletal muscle function may also be associated with frailty status [5, 7, 8]. Respiratory muscle strength may therefore be relevant not only to respiratory function but also to mobility, physical activity, and overall functional status.

Aging is accompanied by decline in inspiratory and expiratory muscle strength [9]. This decline may be partly attributable to reduced chest wall compliance and age-related pulmonary hyperinflation, which may impair diaphragmatic contractile efficiency [10–12]. Age-related loss of skeletal muscle fibers, particularly type II fibers in the internal intercostal muscles, may also contribute to reduced expiratory muscle strength [13]. Collectively, these changes may occur alongside reduced exercise tolerance and physical activity and may provide a physiological context for the relationship between respiratory muscle strength, physical pre-frailty, and functional decline.

Previous studies have reported differences in inspiratory and expiratory muscle strength among frailty subgroups, including robust, pre-frail, and frail older adults, and have suggested that respiratory muscle strength declines with increasing frailty severity [14, 15]. However, evidence remains limited for community-dwelling Japanese older adults classified according to the revised Japanese Cardiovascular Health Study (J-CHS) criteria. In addition, the associations of both inspiratory and expiratory muscle strength with physical pre-frailty and multiple indicators of functional status, including daily functioning, limb muscle strength, walking speed, and skeletal muscle mass, remain incompletely characterized in this population.

Therefore, the primary aim of this cross-sectional study was to examine the association between respiratory muscle strength, assessed using maximal inspiratory pressure (MIP) and maximal expiratory pressure (MEP), and physical pre-frailty among community-dwelling Japanese older adults. The secondary aim was to explore the associations between respiratory muscle strength and multiple indicators of functional status, including the Kihon Checklist (KCL) score, limb muscle strength, walking speed, and skeletal muscle mass. By focusing on physical pre-frailty, this study sought to provide preliminary evidence regarding respiratory muscle strength as a potential correlate of early vulnerability and to inform future longitudinal and interventional studies in community settings.

Methods

Study design, setting, and participants

The participants included 324 individuals aged ≥ 65 years who participated in a community health survey conducted in three locations within Fukushima Prefecture [Minamisoma city ($n=113$), Kagamiishi town ($n=133$), and Fukushima city ($n=78$)] between August 2024 and February 2025. According to the 2020 Population Census of Japan [16], the total population and the proportion aged ≥ 65 years were 59,005 and 36.2% in Minamisoma City, 12,318 and 27.9% in Kagamiishi Town, and 282,693 and 30.4% in Fukushima City, respectively. Study participants were recruited through advertisements published in local community newsletters. No formal priori sample size calculation was performed because this study was based on a community health survey and included all eligible participants who attended the survey and consented to use of their data. The study size was therefore determined by the number of eligible participants available during the study period. The inclusion criteria were age ≥ 65 years at the time of data collection and residence in the community. Those wishing to participate in this study submitted their applications to the research center by phone or mail. All measurements for this study were conducted at community centers within each city, and the study was designed so that participants would travel to the venue on their own on the day of the measurement. Therefore, during the planning stage, we collected information on the locations of measurement venues and the older adults population in each city within Fukushima Prefecture to assess feasibility; as a result, we ultimately selected these three cities and towns as the study areas.

The exclusion criteria were individuals who did not consent to the use of their assessment data for research purposes and those with missing data. Moreover, since the primary objective of the revised analyses was to examine associations with pre-frailty (early vulnerability), participants meeting the revised J-CHS criteria for frailty (score 3–5) were excluded [17]. Of the 324 participants initially recruited, 11 were excluded because they met the revised J-CHS criteria for frailty (score 3–5). Of these 11 participants, two also had missing data for variables required for the present analysis. Consequently, 313 participants were included in the final analytic sample, comprising participants with pre-frailty (score 1–2) and those with robustness (score 0). No additional participants met the exclusion criteria.

Characteristics

Data on age, sex, smoking (current, former, or never), and comorbidities (hypertension, dyslipidemia, cancer, heart disease, stroke, diabetes, respiratory disease, chronic kidney disease, arthritis, and/or others) were collated using a self-administered questionnaire. Additionally, cognitive function was assessed using the Japanese version of the Montreal Cognitive Assessment (MoCA-J) [18]. MoCA-J was administered by a geriatric psychiatrist and/or assessors who were well trained before data collection, and all evaluations were conducted according to a standardized test manual. Physical activity levels were evaluated using the International Physical Activity Questionnaire–Short Form (IPAQ) to measure total weekly physical activity, vigorous-intensity physical activity (VPA), and moderate-intensity physical activity (MPA) [19]. Based on the methodology of previous studies, participants reporting total daily activity exceeding 960 min were excluded from the analysis of IPAQ data. If the reported VPA or MPA exceeded 180 min/day, the reported time was adjusted to 180 min [19]. For data cleaning, VPA was truncated to 180 min/day in 8 participants, and MPA was truncated to 180 min/day in 29 participants.

Respiratory muscle strength

Respiratory muscle strength was measured as the maximal inspiratory pressure (MIP) and maximal expiratory pressure (MEP) using a respiratory muscle strength tester (IOP-01; Kobata Keiki). All measurements were conducted in accordance with the American Thoracic Society/European Respiratory Society guidelines [20]. The participants were seated on a chair with the trunk positioned at a 90° angle to the hips and the feet resting on the

ground. Next, a clip was attached to the nose, and a mouthpiece was placed rigidly between the lips. The MIP was subsequently acquired by measuring the pressure generated during maximal inspiratory effort from the residual volume, while the MEP was acquired by measuring the pressure generated during maximal expiratory effort from the total lung capacity. Inspiratory and expiratory efforts were conducted for at least 1.5 s, and measurements were taken in triplicate, with a repose period of 30 s between executions. Acceptability of each maneuver was judged based on the absence of air leakage around the mouthpiece, appropriate participant effort, and maintenance of maximal pressure for at least 1.5 s. Measurements were repeated until three acceptable maneuvers were obtained. The device automatically assessed whether the variability among the three measurements was within 20%. If the variability exceeded 20%, an error message was displayed, and measurements were repeated until the repeatability criterion was met. The device automatically selected and recorded the highest of the three values satisfying this criterion, which was used for the analysis. The predicted MIP and MEP values were calculated as follows [21]:

Predicted MIP for males = $45.0 - 0.74 \times \text{age (years)} + 0.27 \times \text{height (cm)} + 0.60 \times \text{weight (kg)}$.

Predicted MIP for females = $-1.5 - 0.41 \times \text{age (years)} + 0.48 \times \text{height (cm)} + 0.12 \times \text{weight (kg)}$.

Predicted MEP for males = $25.1 - 0.37 \times \text{age (years)} + 0.20 \times \text{height (cm)} + 1.20 \times \text{weight (kg)}$.

Predicted MEP for females = $-19.1 - 0.18 \times \text{age (years)} + 0.43 \times \text{height (cm)} + 0.56 \times \text{weight (kg)}$.

%MIP and %MEP were calculated by dividing the measured MIP and MEP values by their respective predicted values, expressed as percentages [22].

All respiratory pressure (MIP and MEP), muscle strength, and walking speed measurements were performed by licensed physical therapists. Trained assessors assisted with the procedures and recorded results according to a standardized manual.

Physical pre-frailty

Physical pre-frailty was assessed using the Revised Japanese Cardiovascular Health Study Criteria (J-CHS criteria) [17]. A participant was considered to have physical frailty if they met three or more of the following five criteria: (i) Shrinking: Have you unintentionally lost 2 kg or more in the past 6 months? (“Yes” = 1 point); (ii) Low activity: (a) Do you engage in moderate levels of physical exercise or sports aimed at improving health? and (b) Do you engage in low levels of physical exercise aimed at improving your health? (“No” to both questions, which means “Do neither once a week” = 1 point); (iii) Exhaustion: In the past 2 weeks, have you felt tired without a reason? (“Yes” = 1 point); (iv) Weakness: grip strength < 28 kg in males or 18 kg in females (1 point); and (v) Slowness: gait speed < 1.0 m/s (1 point). Frailty, pre-frailty, and robustness were scored as 3–5, 1–2, and 0 points, respectively. In the present study, participants meeting the J-CHS criteria for frailty (score 3–5) were excluded, and the primary analyses compared participants with pre-frailty (score 1–2) with those with robustness (score 0).

Overall functional status

Overall functional status was assessed using the Kihon Checklist (KCL), grip strength, knee extension strength, comfortable 10-meter walking speed, and skeletal muscle index (SMI). The KCL [23] is a self-administered questionnaire developed by Japan’s Ministry of Health, Labour and Welfare that comprises 25 questions on living conditions and physical/mental function, with “yes” or “no” answers. The KCL consists of seven domains: five items assessing ADLs, five items assessing musculoskeletal function, two items assessing malnutrition, three items assessing oral function, two items assessing social isolation, three items assessing cognitive function, and five items assessing depressive mood. For each question, one point is assigned if the participant reports a problem with functional ability; a higher score indicates more severe problems with functional ability. Grip strength was measured using the Smedley grip dynamometer (GRIP-D, T.K.K5401, Takei Kiki Kogyo Co., Ltd.). Measurements were performed twice for each hand while standing with the elbows extended, and the maximum value was recorded. Knee extension strength was measured using a handheld dynamometer (μ-Tas F-1 A, Anima Co.,

Ltd.). Participants were seated with the hip and knee flexed at 90°, and the dynamometer sensor was placed on the anterior aspect of the distal lower leg immediately proximal to the ankle joint. The trunk and thigh were stabilized to minimize compensatory movement. Participants were instructed to extend the knee maximally against the sensor for approximately 3–5 s. For each participant, the moment arm was measured as the distance from the knee joint axis to the center of the dynamometer sensor. Knee extension torque was calculated by multiplying the force displayed by the dynamometer in newtons by the moment arm in meters. The calculated torque was subsequently normalized to body mass in kilograms and expressed as Nm/kg. Measurements were performed twice for each leg, with sufficient rest between trials, and the maximum value was used for analysis. The comfortable 10-meter walking speed was measured by instructing participants to walk at their normal pace and timing the duration required to walk the central 10 m of a 16-m walking path. SMI was measured using a body composition analyzer (InBody S10, InBody Co., Ltd.). For descriptive purposes, sarcopenia status was retrospectively classified using the available body composition and grip-strength data according to the Asian Working Group for Sarcopenia 2025 consensus criteria [24]. In adults aged ≥ 65 years, sarcopenia requires concurrent low muscle mass and low muscle strength (physical performance is an outcome indicator). Low grip strength is defined as a handgrip strength of < 28 kg in males and < 18 kg in females. Low muscle mass, assessed by BIA, is defined as $ASM/height^2$ (SMI) < 7.0 kg/m² in males and < 5.7 kg/m² in females, with an alternative BIA index of $ASM/BMI < 0.83$ in males and < 0.57 in females. All physical performance and body composition measurements were conducted according to standardized procedures. Grip strength, knee extension strength, and walking speed were measured by licensed physical therapists using a standardized manual. Before data collection, assessors were instructed regarding participant positioning, verbal instructions, measurement trials, and recording procedures to reduce measurement variability.

Statistical analysis

For descriptive statistics of the participants' characteristics, all continuous variables were presented as medians (interquartile range), and categorical variables as n (%). The chi-squared and Mann–Whitney U tests were used for intergroup comparisons of basic characteristics. Fisher's exact test was applied when expected cell counts were low or when any cell contained zero observations.

For the primary analysis, logistic regression models were fitted with physical pre-frailty status as the dependent variable and either MIP or MEP as the independent variable of interest. MIP and MEP were entered into separate models. Model 1 was adjusted for age, sex, body mass index, smoking status, and history of respiratory disease. As a post-hoc sensitivity analysis, Model 2 additionally adjusted for diabetes and MoCA-J score because these clinically relevant potential confounders differed significantly between the physical pre-frailty and robust groups in descriptive comparisons. Adjusted odds ratios and 95% confidence intervals were estimated, and odds ratios for absolute MIP and MEP values were also expressed per 10-cmH₂O increase. The same Model 1 and Model 2 covariate structures were applied to the analyses using %MIP and %MEP instead of the corresponding absolute values. Furthermore, to ascertain the reference values for MIP and MEP related to pre-frailty, receiver operating characteristic (ROC) curve analysis was performed to calculate the cutoff values for MIP and MEP. Cutoff values were selected based on the point at which Youden's index was maximized, and the discriminatory ability of the cutoff values was evaluated using the area under the curve (AUC).

A secondary analysis performed to examine the relationship between respiratory muscle strength and overall functional status entailed multiple regression analysis, with each functional status as the dependent variable and MIP or MEP (in separate models) and age, sex, BMI, smoking, and history of respiratory disease as covariates. Since the secondary analyses evaluated two respiratory muscle strength exposures (MIP and MEP) across five functional outcomes (KCL score, grip strength, knee extension strength, walking speed, and SMI), they were considered exploratory. To account for multiple testing, the Benjamini–Hochberg false discovery rate procedure was applied across the 10 secondary tests. Both unadjusted p-values and FDR-adjusted q-values are presented (Table 4). Because the KCL score is a bounded integer score ranging from 0 to 25, two sensitivity analyses were

performed to assess the robustness of the primary linear regression findings. First, the models were refitted using a normal distribution with an identity link and a robust sandwich covariance estimator. Second, negative binomial regression models with a log link were fitted, treating the KCL score as an integer-valued outcome. MIP and MEP were examined in separate models using the same covariates as in the primary analyses.

For model diagnostics, multicollinearity was assessed using variance inflation factors (VIFs), and logistic model fit was evaluated using the Hosmer–Lemeshow goodness-of-fit test. The linearity assumption between continuous predictors and the logit of the outcome was assessed using the Box–Tidwell approach. Residual histograms, normal probability (P–P) plots, residual-versus-predicted value plots, and Cook’s distance were examined for models using KCL as the dependent variable to assess residual normality, homoscedasticity, and influential observations.

All analyses were conducted using SPSS Statistics (version 30.0) for Windows (IBM, Armonk, NY, USA). The level of statistical significance was set at $p < 0.05$.

Results

Characteristics

The participants’ characteristics are listed in Table 1. A total of 313 participants were included in the final analysis. Their median age was 75 (72–79) years, the proportion of females was 75.1%, and the median BMI was 22.84 (20.78–25.06) kg/m². Of the 313 participants, 141 (45.0%) were assigned to the Pre-frailty group and 172 (55.0%) to the robust group. The MoCA-J scores ($p = 0.002$), MIP ($p < 0.001$), MEP ($p < 0.001$), %MIP ($p = 0.024$), %MEP ($p = 0.018$), total KCL score ($p < 0.001$), grip strength ($p < 0.001$), knee extension strength ($p = 0.002$), and comfotable 10-meter walking speed ($p < 0.001$), were significantly lower in the pre-frailty group compared with the robust group. The prevalence of sarcopenia differed markedly between the two groups. No participants in the robust group met the criteria for sarcopenia, whereas 39 participants (27.7%) in the pre-frailty group were classified as sarcopenic. Given the presence of zero events in one group, group differences were assessed using Fisher’s exact test, which indicated a statistically significant difference ($p < 0.001$).

Association between respiratory muscle strength and physical pre-frailty

Table 2 shows the associations of absolute MIP and MEP values with physical pre-frailty. In the crude models, higher MIP and MEP were each significantly associated with lower odds of physical pre-frailty (both $p < 0.001$). These associations remained statistically significant in Model 1, which adjusted for age, sex, body mass index, smoking status, and history of respiratory disease (MIP, $p < 0.001$; MEP, $p = 0.002$).

In the post-hoc sensitivity analysis, Model 2 additionally adjusted for diabetes and MoCA-J score. The associations remained statistically significant after this additional adjustment. The adjusted odds ratios per 10-cmH₂O increase were 0.842 for MIP (95% CI, 0.745–0.951; $p = 0.007$) and 0.842 for MEP (95% CI, 0.737–0.961; $p = 0.010$). The directions and magnitudes of these associations were generally consistent with those observed in Model 1.

Similar findings were obtained from the analyses using percentage-predicted respiratory muscle strength values (Table 3). In Model 1, both %MIP ($p = 0.008$) and %MEP ($p = 0.007$) were significantly associated with physical pre-frailty. After additional adjustment for diabetes and MoCA-J score in Model 2, the associations remained statistically significant for both %MIP (OR, 0.993; 95% CI, 0.987–0.999; $p = 0.028$) and %MEP (OR, 0.989; 95% CI, 0.980–0.998; $p = 0.018$).

For all logistic regression models, the variance inflation factors for the predictor variables were < 2.0 , indicating no substantial multicollinearity. The Hosmer–Lemeshow goodness-of-fit tests indicated acceptable model

Table 1 Characteristics of the study participants

	All participants (<i>n</i> =313)	Pre-Frailty group (<i>n</i> =141)	Robust group (<i>n</i> =172)	<i>p</i> -value
Age, year	75 (72–79)	76 (72–80)	75 (72–78)	0.111
Sex, female, <i>n</i> (%)	235 (75.1)	108 (76.6)	127 (73.8)	0.601
Height, cm	153.10 (148.20–159.50)	151.90 (147.25–158.12)	153.9 (149.3–160.4)	0.028
Weight, kg	53.8 (47.8–60.50)	53.3 (47.4–60.20)	54.5 (49.0–61.3)	0.182
BMI, kg/m ²	22.84 (20.78–25.06)	22.58 (20.29–25.25)	23.1 (21.1–24.9)	0.868
Smoking, <i>n</i> (%)				
Current	6 (1.9)	3 (2.1)	3 (1.7)	0.116
Former	60 (19.2)	20 (14.2)	40 (23.3)	
Never	247 (78.9)	118 (83.7)	129 (75.0)	
Comorbidities, <i>n</i> (%)				
Hypertension	130 (41.5)	64 (45.4)	66 (38.4)	0.249
Dyslipidemia	78 (24.9)	33 (23.4)	45 (26.2)	0.601
Cancer	43 (13.7)	24 (17.0)	19 (11.0)	0.140
Cardiovascular disease	46 (14.7)	22 (15.6)	24 (14.0)	0.749
Stroke	4 (1.3)	2 (1.4)	2 (1.2)	0.611
Diabetes	43 (13.7)	31 (22.0)	12 (7.0)	<0.001
Respiratory disease	9 (2.9)	6 (4.3)	3 (1.7)	0.308
CKD	14 (4.5)	6 (4.3)	8 (4.7)	0.545
Arthritis	25 (8.0)	14 (9.9)	11 (6.4)	0.297
MoCA-J, points	25 (22–27)	24 (21–27)	26 (23–27)	0.002
Respiratory muscle strength				
MIP, cmH ₂ O	55.1 (42.0–70.1)	52.6 (38.4–64.5)	58.6 (43.9–75.5)	<0.001
MEP, cmH ₂ O	57.2 (46.3–75.1)	52.6 (43.7–66.2)	62.2 (48.9–81.0)	<0.001
%MIP	109.3 (78.4–138.0)	103.5 (74.8–131.5)	110.4 (84.0–143.1)	0.024
%MEP	84.0 (68.8–102.1)	80.9 (64.5–99.7)	86.4 (71.5–106.9)	0.018
Functional status				
KCL score, points	4 (2–6)	5 (3–9)	3 (2–5)	<0.001
Grip strength, kg	24.3 (21.6–29.0)	23.9 (19.7–27.0)	24.8 (22.3–30.3)	<0.001
Knee extension strength, Nm/kg	1.40 (1.18–1.70)	1.35 (1.16–1.58)	1.48 (1.24–1.74)	0.002
Comfortable 10-meter walking speed, m/s	1.51 (1.36–1.65)	1.45 (1.29–1.56)	1.56 (1.40–1.69)	<0.001
SMI, kg/m ²	6.3 (5.8–7.2)	6.2 (5.8–7.0)	6.4 (5.8–7.2)	0.144
ASM/BMI	0.85 (0.75–0.99)	0.83 (0.73–0.98)	0.88 (0.77–1.08)	0.189
Sarcopenia	39 (12.5)	39 (27.7)	0 (0.0)	<0.001*
Physical activity				
VPA, METs· min/week	0 (0–78)	0 (0–36)	0 (0–960)	0.053
MPA, METs· min/week	0 (0–480)	0 (0–312)	0 (0–624)	0.085
Total physical activity, METs· min/week	1575.00 (594.00–3052.50)	1447.80 (396.00–3204.45)	1694.1 (759.2–3025.5)	0.131

Continuous variables are presented as medians (interquartile range) and categorical variables as *n* (%)

*Fisher's exact test was used because of a zero cell (0 counts in the Robust group)

BMI, body mass index; CKD, chronic kidney disease; MoCA-J, Japanese version of the Montreal Cognitive Assessment; MIP, maximal inspiratory pressure; MEP, maximal expiratory pressure; KCL, Kihon Checklist; SMI, skeletal muscle index; VPA, vigorous-intensity physical activity; MPA, moderate-intensity physical activity

fit (all $p > 0.05$). The Box–Tidwell assessments identified no substantial violations of the linearity assumption between the continuous predictors and the logit of physical pre-frailty.

ROC curve based on MIP and MEP for the discrimination of pre-frailty status

As shown in Fig. 1, both MIP ($p = 0.001$) and MEP ($p < 0.001$) demonstrated significant discriminative performances. The MIP yielded an AUC of 0.61, while the MEP showed a similar AUC of 0.62. The exploratory cutoff values determined by Youden's index were 55.1 cmH₂O for MIP and 61.2 cmH₂O for MEP. At these thresholds,

Table 2 Association Between Respiratory Muscle Strength and Pre-frailty (Absolute Value Model)

	B (per 1 cmH ₂ O)	OR (per 1 cmH ₂ O)	95% CI (per 1 cmH ₂ O)	OR* (per 10 cmH ₂ O)	95% CI * (per 10 cmH ₂ O)	p-value
Crude model						
MIP model	-0.020	0.981	0.970–0.992	0.825	0.737–0.923	<0.001
MEP model	-0.019	0.981	0.971–0.992	0.826	0.745–0.923	<0.001
Adjusted model 1^a						
MIP model	-0.020	0.980	0.968–0.992	0.817	0.722–0.923	<0.001
MEP model	-0.019	0.981	0.969–0.993	0.826	0.730–0.932	0.002
Adjusted model 2^b						
MIP model	-0.017	0.983	0.971–0.995	0.842	0.745–0.951	0.007
MEP model	-0.017	0.983	0.970–0.996	0.842	0.737–0.961	0.010

OR, odds ratio; CI, confidence interval; MIP, maximal inspiratory pressure; MEP, maximal expiratory pressure

a Model adjusted for covariates including age, sex, BMI, smoking, and history of respiratory disease

b Model adjusted for covariates including age, sex, BMI, smoking, history of respiratory disease, diabetes, and MoCA-J score

* ORs per 10 cmH₂O increase were calculated by exponentiating the regression coefficient multiplied by 10 [$\exp(10 \times B)$]

Table 3 Association Between Respiratory Muscle Strength and Pre-frailty (Percent-Predicted Model)

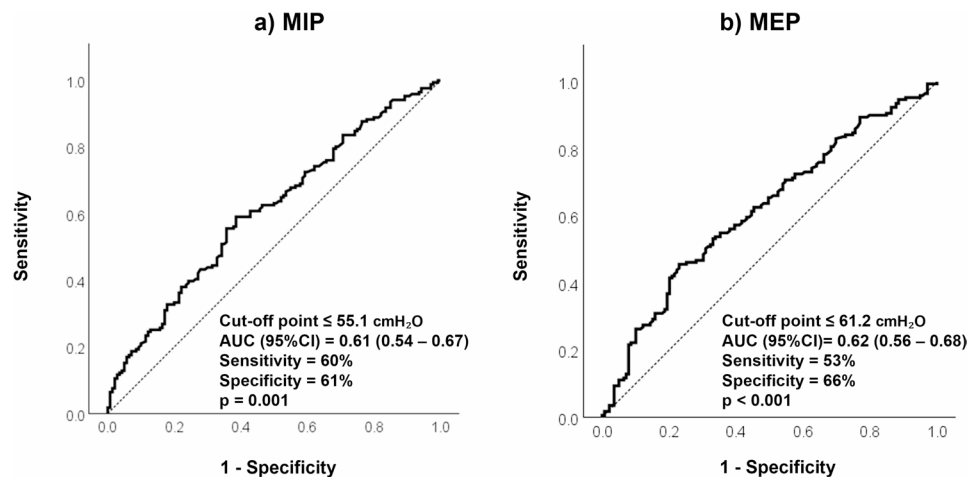
	B	OR	95% CI	p-value
Crude model				
%MIP model	-0.007	0.993	0.988–0.999	0.022
%MEP model	-0.011	0.989	0.982–0.997	0.009
Adjusted model 1^a				
%MIP model	-0.008	0.992	0.986–0.998	0.008
%MEP model	-0.012	0.988	0.980–0.997	0.007
Adjusted model 2^b				
%MIP model	-0.007	0.993	0.987–0.999	0.028
%MEP model	-0.011	0.989	0.980–0.998	0.018

OR, odds ratio; CI, confidence interval; MIP, maximal inspiratory pressure; MEP, maximal expiratory pressure

a Model adjusted for covariates including age, sex, BMI, smoking, and history of respiratory disease

b Model adjusted for covariates including age, sex, BMI, smoking, history of respiratory disease, diabetes, and MoCA-J score.

Fig. 1 ROC curve based on the MIP and MEP for the discrimination of pre-frailty. **a)** ROC curve based on the MIP for the discrimination of pre-frailty **b)** ROC curve based on the MEP for the discrimination of pre-frailty ROC, receiver operating characteristic; MIP, maximal inspiratory pressure; MEP, maximal expiratory pressure; CI, confidence interval



MIP demonstrated a sensitivity of 60% and specificity of 61%, whereas MEP showed a sensitivity of 53% and specificity of 66%. Given the modest AUC values, these cutoff values should be regarded as exploratory reference points rather than clinically established thresholds.

Association between respiratory muscle strength and overall functional status

The relationship between respiratory muscle strength and overall functional status is shown in Table 4; Figs. 2 and 3. Lower MIP was significantly associated with higher total KCL scores ($p=0.031$), lower grip strength ($p<0.001$), lower knee extension strength ($p<0.001$), lower comfortable 10-meter walking speed ($p=0.011$), and lower SMI ($p=0.020$). Similarly, lower MEP was significantly associated with higher total KCL scores ($p=0.032$), lower grip strength ($p=0.017$), lower knee extension strength ($p<0.001$), and lower comfortable 10-meter walking speed ($p<0.001$). However, the association between MEP and SMI was not statistically significant after adjustment for covariates ($p=0.513$). Residual diagnostics for models using KCL as the dependent variable demonstrated no major violations of normality or homoscedasticity assumptions. After applying the Benjamini–Hochberg false discovery rate correction across the 10 adjusted secondary tests, the associations with borderline unadjusted p -values remained statistically significant, including MIP with KCL score, MIP with SMI, and MEP with KCL score. Moreover, the association between MEP and SMI remained non-significant.

Because the KCL score is a bounded integer outcome, additional sensitivity analyses were performed. When robust sandwich covariance estimators were used, the associations of MIP and MEP with KCL score remained statistically significant (MIP: $B=-0.018$, 95% CI -0.036 to -0.001 , $p=0.041$; MEP: $B=-0.020$, 95% CI -0.038 to -0.002 , $p=0.029$). In contrast, although the estimated associations remained in the same direction in the negative binomial regression models, they were not statistically significant (MIP: $RR=0.996$, 95% CI 0.989 – 1.002 , $p=0.166$; MEP: $RR=0.995$, 95% CI 0.989 – 1.001 , $p=0.129$).

Table 4 Association Between Respiratory Muscle Strength and Overall Functional Status

	Crude model			Adjusted model*			FDR-adjusted q-value†
	B	95% CI	p-value	B	95% CI	p-value	
KCL score							
MIP model	-0.026	-0.042 - -0.009	<0.001	-0.019	-0.037–0.002	0.031	0.036
MEP model	-0.028	--0.044 - -0.012	<0.001	-0.020	-0.038- -0.002	0.032	0.036
Grip strength							
MIP model	0.115	0.086–0.144	<0.001	0.039	0.018–0.059	<0.001	<0.001
MEP model	0.121	0.093–0.149	<0.001	0.026	0.005–0.047	0.017	0.028
Knee extension strength							
MIP model	0.006	0.004–0.008	<0.001	0.005	0.003–0.007	<0.001	<0.001
MEP model	0.008	0.006–0.009	<0.001	0.007	0.005–0.009	<0.001	<0.001
Comfortable 10-meter walking speed							
MIP model	0.001	0.000–0.003	0.024	0.002	0.000–0.003	0.011	0.022
MEP model	0.002	0.001–0.003	<0.001	0.003	0.001–0.004	<0.001	<0.001
SMI							
MIP model	0.016	0.011–0.020	<0.001	0.004	0.001–0.007	0.020	0.029
MEP model	0.015	0.011–0.020	<0.001	0.001	-0.002–0.004	0.513	0.513

CI, confidence interval; MIP, maximal inspiratory pressure; MEP, maximal expiratory pressure; KCL, Kihon Checklist; SMI, skeletal muscle index

* Model adjusted for covariates including age, sex, BMI, smoking, and history of respiratory disease

†FDR-adjusted q-values were calculated for the 10 adjusted secondary analyses. For p -values reported as <0.001 , FDR-adjusted q -values were calculated using exact p -values from the statistical output

Fig. 2 Scatter plot of maximal inspiratory pressure and overall functional status. **a)** Association between the MIP and KCL score; **b)** Association between the MIP and grip strength; **c)** Association between the MIP and knee extension strength; **d)** Association between the MIP and 10-m walking speed; **e)** Association between the MIP and SMIMIP, maximal inspiratory pressure; KCL, Kihon Checklist; SMI, skeletal muscle index

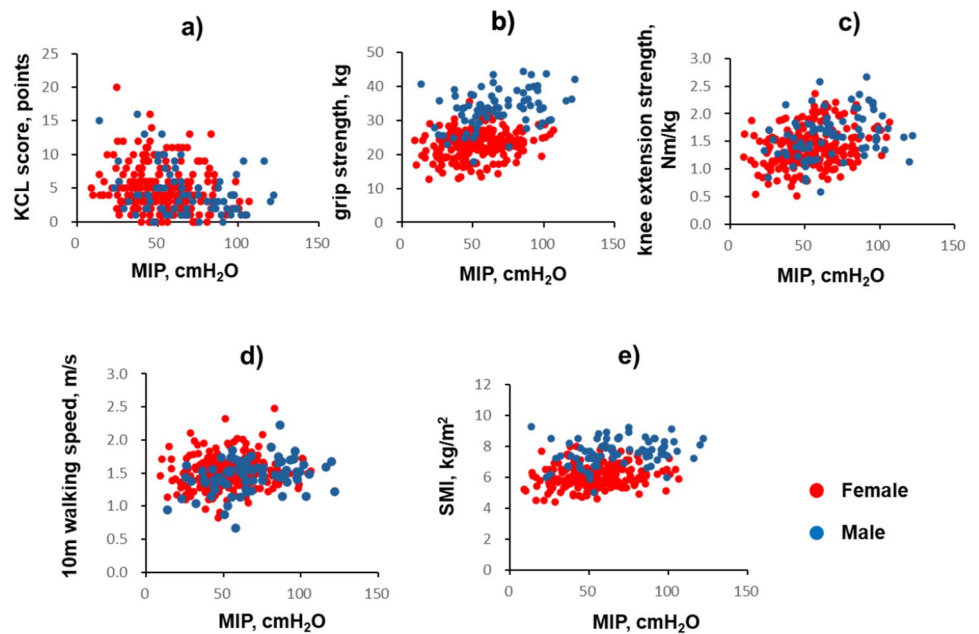
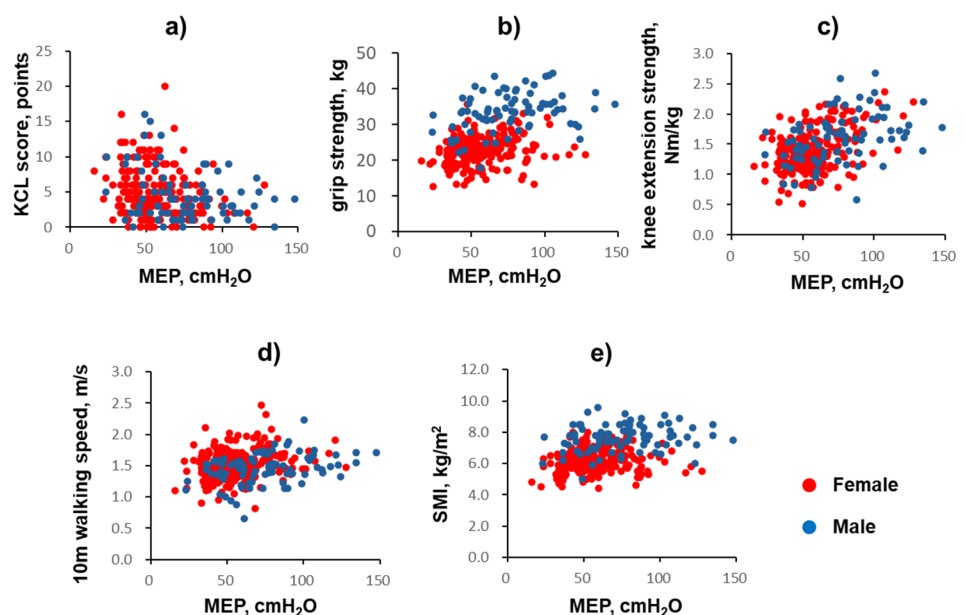


Fig. 3 Scatter plot of maximal expiratory pressure and overall functional status. **a)** Association between MEP and KCL score; **b)** Association between MEP and grip strength; **c)** Association between MEP and knee extension strength; **d)** Association between MEP and 10 m walking speed; **e)** Association between MEP and SMIMEP, maximal expiratory pressure; KCL, Kihon Checklist; SMI, skeletal muscle index



Discussion

The principal findings of this study are as follows. Among community-dwelling older adults in Japan, lower MIP and MEP were significantly associated with a higher likelihood of physical pre-frailty. Moreover, lower respiratory muscle strength was associated with poorer overall functional status, as reflected by higher KCL scores and lower grip strength, knee extension strength, walking speed, and skeletal muscle mass, although the adjusted association between MEP and SMI was not statistically significant.

The observed association between respiratory muscle strength and pre-frailty is broadly consistent with previous reports demonstrating lower inspiratory and expiratory muscle strength in frail individuals compared with

non-frail counterparts. In particular, prior studies have suggested that respiratory muscle strength declines with increasing frailty severity and may reflect vulnerability-related reductions in physiological reserve among community-dwelling older adults. Although direct comparisons across studies should be made cautiously because of differences in case definitions and target populations, our findings extend this body of evidence by showing that lower respiratory muscle strength is already associated with an earlier stage of vulnerability (pre-frailty) in a community-based sample [14, 15].

As the odds ratios for MIP and MEP are expressed per 1-cmH₂O increase, the magnitude of association appears modest at the unit level. However, when scaled to a 10-cmH₂O increase, the adjusted odds ratios are approximately 0.82 for MIP and 0.83 for MEP, suggesting that clinically meaningful differences in respiratory muscle strength may be associated with decreased odds of pre-frailty. On the other hand, the modest AUC values and only moderate sensitivity and specificity observed in the present study indicate that MIP and MEP alone have limited discriminative capacity for identifying pre-frailty. Given the multifactorial nature of pre-frailty, this is not unexpected. Therefore, although respiratory muscle strength may be associated with early vulnerability, the use of MIP and MEP as standalone screening tools for pre-frailty requires cautious and conservative interpretation. Rather, these measures may be more appropriately positioned as complementary components within a multidimensional assessment framework. Accordingly, the ROC-derived cutoff values should be interpreted as exploratory reference values rather than clinically definitive thresholds. These values were presented to describe the discriminatory characteristics of MIP and MEP in this sample and not to propose their use as independent diagnostic or screening criteria for pre-frailty.

Beyond discrimination metrics, our findings may be clinically meaningful because pre-frailty represents an intermediate and potentially modifiable stage between robustness and frailty. In the phenotype model, pre-frailty is defined by the presence of one or two frailty components and reflects an early vulnerability state that can progress to frailty but may also improve or revert, highlighting its relevance as a pragmatic target for prevention [5]. Indeed, transitions between frailty states have been documented in community settings, supporting the concept that frailty is dynamic rather than fixed [7, 8]. Importantly, evidence indicates that prognostic risk is already elevated at the pre-frail stage. A meta-analysis by Veronese et al. reported that both frailty and pre-frailty are associated with higher risks of cardiovascular disease morbidity and mortality compared with robustness, underscoring the importance of prevention strategies that target not only established frailty but also earlier vulnerability [25]. Together, these data suggest that preventing or delaying progression from robustness to pre-frailty—and from pre-frailty to frailty—may have implications for both functional status and prognosis. From this perspective, identifying feasible correlates of early vulnerability in community settings (such as respiratory muscle strength) may help inform multidimensional prevention strategies, including exercise-based approaches proposed to manage or delay frailty-related trajectories [1].

The present findings should be interpreted cautiously because the observed associations may partly reflect parallel age-related changes rather than causal or fully independent relationships. Although our multivariable models were adjusted for age and sex and additionally examined percent-predicted respiratory pressures, residual confounding related to age-associated decline in overall physiological reserve and multisystem function cannot be excluded. Aging is accompanied by structural and mechanical changes in the respiratory system, including reduced diaphragmatic efficiency and altered respiratory muscle properties [10–13]. These changes may coexist with declines in muscle strength, mobility, exercise tolerance, and broader functional status, mediated by reduced ventilatory efficiency and decreased blood flow to the extremities [26–30]. However, because these mechanisms were not directly examined in this cross-sectional study, they should be considered as a possible physiological context rather than definitive explanations for the present findings. Accordingly, our results are best interpreted as cross-sectional associations consistent with early vulnerability, and longitudinal studies are needed to clarify temporal ordering and determine whether respiratory muscle weakness precedes transitions from robustness to prefrailty and ultimately to frailty.

Based on the hypothesis that respiratory muscle weakness may be linked to pre-frailty through broader impairments in physical and ADL-related function rather than isolated respiratory dysfunction, we examined

associations with multiple indicators of functional status. Consistent with this hypothesis, respiratory muscle strength in the present study was significantly associated not only with pre-frailty status but also with a broad range of functional measures reflecting overall functional independence. These findings are consistent with the concept that respiratory muscle strength may be one of the several factors associated with early vulnerability in community-dwelling older adults. However, the associations between respiratory muscle strength and KCL score were sensitive to the assumed outcome distribution. Although the associations remained statistically significant when robust sandwich covariance estimators were used, they were not statistically significant in the negative binomial regression models. Therefore, the KCL findings should be interpreted cautiously.

The focus on physical pre-frailty, rather than sarcopenia, reflects the clinical objective of identifying early vulnerability at the community level. Although sarcopenia is an important construct reflecting muscle health and partially overlaps with physical frailty, pre-frailty captures a broader phenotype that includes weakness, slowness, exhaustion, low physical activity, and weight loss. Respiratory muscle weakness may be related not only to reduced skeletal muscle function but also to exercise intolerance, activity limitation, and broader functional vulnerability. Accordingly, physical pre-frailty was considered more closely aligned with the primary objective of the present study. Sarcopenia status was therefore included as descriptive background information and was not treated as a primary or secondary outcome.

This study has several strengths. First, both MIP and MEP were assessed, allowing inspiratory and expiratory muscle function to be examined separately. Second, physical pre-frailty was classified using the revised J-CHS criteria in a community-based Japanese sample, enabling investigation of respiratory muscle strength in relation to early vulnerability among community-dwelling older adults. Third, respiratory muscle strength was evaluated not only in relation to physical pre-frailty but also in association with multiple indicators of functional status, including KCL score, limb muscle strength, walking speed, and skeletal muscle mass. Fourth, the robustness of the primary findings was examined using percentage-predicted respiratory pressure values in addition to absolute MIP and MEP values. Finally, false discovery rate correction was applied to the exploratory secondary analyses to account for multiple testing.

Limitations

This study has several limitations. First, since the participants were recruited from three selected municipalities in Fukushima Prefecture based on the feasibility of conducting community-based measurements and the accessibility of measurement venues, the sample may not fully represent all community-dwelling older adults in Japan. Regional differences in population aging, transportation access, healthcare resources, social participation, and health behaviors may influence both respiratory muscle strength and functional status. Therefore, the generalizability of our findings should be interpreted with caution. Future studies should include more geographically diverse populations and examine whether similar associations are observed across different community settings. Second, we did not collect information on certification status under Japan's Long-Term Care Insurance (LTCI) system; therefore, we could not explicitly exclude participants with certified care needs. This may have introduced selection heterogeneity and limits the interpretation of pre-frailty as a stage strictly preceding certified care need. Third, because of the cross-sectional design, temporal ordering and causal relationships between respiratory muscle strength and pre-frailty or overall functional status cannot be determined; longitudinal studies are needed to clarify whether reduced respiratory muscle strength precedes transitions from robustness to pre-frailty and subsequent functional decline. Furthermore, the physical pre-frailty and robust groups differed in diabetes prevalence and cognitive function, as assessed using the MoCA-J. We therefore performed a post-hoc sensitivity analysis in which Model 2 additionally adjusted for diabetes and MoCA-J score, and the associations were generally consistent with those observed in Model 1. Nevertheless, residual confounding due to unmeasured or incompletely measured metabolic, cardiovascular, musculoskeletal, cognitive, or other health-related factors cannot be excluded. Fourth, because participants meeting the revised J-CHS criteria for frailty (score 3–5) were excluded from the present analyses, the relationship between respiratory muscle strength and progression to overt frailty

could not be examined in this dataset. Fifth, because no formal priori sample size calculation was performed, the study may have been underpowered for some secondary or sensitivity analyses. Therefore, the results of these analyses should be interpreted as exploratory. In addition, although the associations between respiratory muscle strength and KCL score remained statistically significant when robust covariance estimators were used, they were not statistically significant in the negative binomial regression models. Therefore, the KCL findings may be sensitive to model specification and should be interpreted cautiously.

The present cross-sectional findings do not establish whether respiratory muscle weakness is a causal contributor to pre-frailty, a marker of generalized physical decline, or a potentially modifiable therapeutic target. Lower MIP and MEP may reflect broader age-related declines in physiological reserve, skeletal muscle function, physical activity, and functional independence rather than an isolated respiratory mechanism. Conversely, respiratory muscle weakness could plausibly contribute to reduced exercise tolerance and activity limitation, thereby participating in the development of early vulnerability. As this study could not determine temporal ordering or causal direction, these possibilities should be regarded as hypotheses for future research. Longitudinal studies are needed to clarify whether respiratory muscle weakness precedes transitions from robustness to pre-frailty, and interventional studies are required to determine whether improving respiratory muscle strength contributes to frailty prevention or functional improvement.

Another important methodological consideration is the conceptual overlap between the J-CHS criteria for physical pre-frailty and some functional measures examined in this study. The J-CHS criteria include grip strength and walking speed as components of frailty status, while these variables were also examined as indicators of functional status. Therefore, associations involving grip strength and walking speed should not be interpreted as fully independent external validation findings, but rather as complementary analyses describing how respiratory muscle strength relates to the functional domains embedded in physical pre-frailty. Similarly, sarcopenia was presented only as descriptive background information because its diagnostic criteria include low muscle strength and low muscle mass, which partially overlap with frailty-related constructs. Accordingly, the sarcopenia findings should be interpreted cautiously and not as independent evidence beyond the primary pre-frailty analysis.

Conclusion

This cross-sectional study showed that lower respiratory muscle strength (MIP and MEP) was associated with a higher likelihood of pre-frailty and poorer overall functional status in community-dwelling Japanese older adults. Given the multifactorial nature of prefrailty and the modest discriminative performance observed, respiratory muscle strength is likely one of the several factors associated with early vulnerability and may be best positioned as a complementary component within a multidimensional assessment framework rather than a standalone screening tool. As our study design did not permit causality or temporal ordering to be determined, longitudinal studies are warranted to clarify whether respiratory muscle weakness precedes transitions from robustness to prefrailty and to evaluate its potential role as a modifiable target in prevention strategies.

Abbreviations

ADL	Activities of Daily Living
AUC	Area Under the Curve
AWGS	Asian Working Group for Sarcopenia
BMI	Body Mass Index
IPAQ	International Physical Activity Questionnaire
KCL	Kihon Checklist
MEP	Maximal Expiratory Pressure
MIP	Maximal Inspiratory Pressure

MoCA-J	Montreal Cognitive Assessment-Japanese version
MPA	moderate-intensity physical activities
ROC	receiver operating characteristic
SMI	skeletal muscle index
VIF	variance inflation factor
VPA	vigorous-intensity physical activities
J-CHS	Japanese Cardiovascular Health Study
SPSS	Statistical Package for the Social Sciences

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Data Availability The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate The research protocol was reviewed and approved by Fukushima Medical University (approval No.: General 2022-123). Written informed consent was obtained from all participants. This study was conducted according to the guidelines of the Declaration of Helsinki

Consent for publication Not applicable

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

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