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Cardiopulmonary Exercise Testing Profile and Peak Work Rate-Based Screening for Low Fitness in Individuals with Stroke-Related Disability in South Korea

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Abstract

Background: Low cardiorespiratory fitness after stroke limits physical activity and independence; however, cardiopulmonary exercise testing profiles, including ventilatory indices and comparisons with Korean reference values, have not been described in individuals with stroke in South Korea. **Methods:** This cross-sectional study analyzed baseline incremental cycle ergometer tests of 45 individuals with stroke from a clinical trial (KCT0005782). **Results:** Peak oxygen uptake was 16.8 ± 5.5 mL/kg/min, corresponding to 54.2% of the US-derived and 57.8% of the Korean reference values; 37.8% fell below 15 mL/kg/min, a published threshold proposed for independent living. Only 13.3% reached a peak respiratory exchange ratio of ≥1.10, indicating symptom-limited rather than maximal capacity. Age ($\beta = -0.42$) and balance function ($\beta = 0.39$) were associated with peak oxygen uptake. A peak work rate of ≤48.3 W (failure to complete the 50 W stage) identified low capacity with an area under the curve of 0.95 (apparent sensitivity, 94.1%; specificity, 89.3%; bootstrap optimism-corrected, 89.8% and 87.6%), whereas the American College of Sports Medicine equation showed significant proportional bias. **Conclusions:** Fitness was approximately half that of healthy Koreans, and peak cycling work rate may be a practical preliminary screening indicator where gas analysis is unavailable, pending external validation.

Keywords: stroke rehabilitation; exercise test; oxygen consumption; postural balance; reference values; mass screening

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1. Introduction

Stroke is a leading cause of death and disability worldwide. In 2021, an estimated 93.8 million people were living with stroke and 11.9 million new strokes occurred, with incidence and prevalence rising in East Asia [1]. In South Korea, stroke is the second leading cause of death; although the age-standardized incidence has declined, the total number of stroke events continues to increase because of rapid population aging [2]. Consequently, the number of individuals living in the community with stroke is growing, and long-term maintenance of function and secondary prevention have become central goals of rehabilitation. The American Heart Association and American Stroke Association recommend regular aerobic exercise for stroke survivors and pre-participation exercise testing to ensure safe and individualized exercise prescription [3]. In Korea, the evidence-based clinical practice guideline for stroke rehabilitation has also been revised to emphasize rehabilitation for motor recovery [4].

Cardiorespiratory fitness in stroke survivors is markedly lower than that of age- and sex-matched healthy individuals. A systematic review reported peak oxygen uptake (VO_2peak) values of 8–22 mL/kg/min after stroke, corresponding to only 26–87% of those of healthy controls [5]. This reduction reflects a combination of central factors, such as comorbid cardiovascular disease, and peripheral factors, including atrophy of the paretic muscles, changes in muscle fiber type, increased intramuscular fat, and reduced capillary density [6,7]. In a systematic review dominated by Asian patients, the prevalence of sarcopenia increased from 15.8% before stroke to 51.6% within 1 month of onset [7]. Low cardiorespiratory fitness restricts daily physical activity [8] and is associated with post-stroke fatigue [9], creating a vicious cycle of further deconditioning. Moreover, cardiorespiratory fitness is a strong independent predictor of mortality regardless of age, sex, and race, with each 1-MET increase associated with a 14% lower risk of death [10,11]. When VO_2peak falls below approximately 15–18 mL/kg/min, maintaining independent daily living becomes difficult [12]. Accurate assessment of cardiorespiratory fitness in individuals with stroke is therefore essential for both functional prognosis and exercise prescription.

Cardiopulmonary exercise testing (CPET) with respiratory gas analysis is the gold standard for assessing cardiorespiratory fitness. In addition to VO_2peak, CPET provides indices that help to interpret the mechanisms of exercise limitation, such as ventilatory efficiency (the minute ventilation/carbon dioxide output [$\dot{V}_E/VCO_2$] slope), the oxygen uptake efficiency slope (OUES), and end-tidal carbon dioxide pressure [13,14]. Among these, OUES and the $\dot{V}_E/VCO_2$ slope are submaximal indices that depend less on maximal effort and are therefore particularly useful in populations that rarely reach maximal exercise [14,15]. However, CPET results in stroke research have mostly focused on VO_2peak and heart rate, and ventilatory responses remain poorly characterized [16]. A systematic review of 60 studies also noted that most did not adequately follow CPET guidelines, making comparisons between studies difficult, and a review of measurement properties found little high-quality evidence [17,18]. Cycle ergometry is the most widely used test modality in stroke because it is safe for individuals with balance impairment [17,19].

Four gaps remain in the existing literature. First, most data have been derived from North American and European cohorts [5,16,19,20], and comprehensive CPET profiles including ventilatory indices are lacking for community-dwelling individuals with stroke in South Korea. Moreover, the age-related decline in cardiorespiratory fitness is smaller in healthy Koreans than in Western populations, so percent-predicted values calculated from Western equations may misrepresent the degree of impairment in Koreans [21]; no study has compared the fitness of Korean individuals with stroke against Korean reference values. Second, the effects of age and sex on post-stroke cardiorespiratory fitness are inconsistent; for example, an analysis of 62 individuals with chronic stroke found no sex difference in VO_2peak [16]. Third, gas analyzers are rarely available in community rehabilitation settings, and fitness is often estimated from work rate alone, typically with the American College of Sports Medicine (ACSM) leg cycling equation [22]. This equation assumes the mechanical efficiency of healthy individuals, and its validity in stroke, in which exercise efficiency is altered, has not been sufficiently tested. In Korea, two-thirds of community-dwelling individuals with stroke exercise, yet only 21% have ever used a community exercise facility, with concerns about exercise-related accidents and a lack of facilities as the main barriers [23]. A simple and safe fitness screening tool applicable in community settings is therefore needed. Fourth, fitness levels among individuals with stroke are highly heterogeneous, and identifying fitness subgroups could inform future individualized exercise approaches.

Accordingly, this study aimed, in community-dwelling individuals with stroke in South Korea, to (1) comprehensively describe the CPET profile, including ventilatory efficiency

and OUES, and its relative level against US-derived and Korean reference values and by sex; (2) examine age-related differences and factors associated with VO_2peak; (3) evaluate the accuracy of peak cycling work rate for identifying individuals with a VO_2peak below 15 mL/kg/min, a published threshold proposed for independent living, and the agreement of the ACSM metabolic equation; and (4) explore CPET-derived clusters using unsupervised cluster analysis. We hypothesized that VO_2peak would be substantially lower than predicted values, that age would be the strongest correlate, and that peak cycling work rate would identify individuals with low fitness with high accuracy.

2. Materials and Methods

2.1. Study Design and Participants

This cross-sectional study analyzed baseline data from an exercise intervention trial registered with the Clinical Research Information Service (CRIS) of the Republic of Korea (KCT0005782), and it is reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement [24]. The Institutional Review Board of the National Rehabilitation Center approved the protocol (approval number NRC014022015), and all participants provided written informed consent before participation. The trial was conducted in 2015, and its registration with CRIS (14 January 2021) was completed after data collection had ended. The participants in the present analysis were drawn from the same 2015 trial cohort as those in a previously published randomized trial [25], which compared multicomponent exercise with or without power training and reported post-intervention changes in cardiorespiratory fitness, physical function, and muscle strength. The present study used only the baseline (pre-intervention) data of this cohort and reports analyses that were not included in that publication: the complete CPET profile, including ventilatory indices and OUES; comparisons with US-derived and Korean reference values; factors associated with VO_2peak; the accuracy of peak work rate for identifying low fitness, with internal validation of the cut-off; agreement of the ACSM equation; and exploratory clustering. All CPET variables were recalculated from the raw data for the present analysis.

Participants were individuals with stroke who were enrolled in the exercise program at the rehabilitation sports center of N Hospital in Seoul, South Korea. The inclusion criteria were (1) a diagnosis of stroke, (2) the ability to follow verbal instructions and communicate, and (3) voluntary participation. The exclusion criteria were (1) neurological disorders other than stroke (e.g., Parkinson's disease), (2) orthopedic problems of the lower extremities, and (3) other cardiopulmonary diseases. This criterion referred to cardiopulmonary diseases other than stroke; the specific diagnoses were not itemized in the trial records available for this analysis. Participants with elevated blood pressure were not excluded (see Section 3.1). The analysis included 45 participants (29 men and 16 women) whose baseline CPET was performed between 5 June and 9 July 2015; all participants with an analyzable baseline CPET record were included, and screening logs (numbers approached and screened) were not available for this secondary analysis. All 45 baseline tests were included in the analyses of peak variables; slope indices and $\Delta VO_2/\Delta WR$ were available for 44 and 30 tests, respectively (Section 2.3). Clinical characteristics, including stroke type, side of hemiparesis, time since stroke onset, Berg Balance Scale (BBS) score, 6 min walk distance (18 m course), Timed Up and Go (TUG) time, Korean version of the Modified Barthel Index (K-MBI), Korean Trunk Impairment Scale (K-TIS), and isometric knee extension strength of the paretic leg (HUR, Kokkola, Finland), were obtained from the trial records; these data were missing for one participant (6 min walk distance for two). Information on the use of walking aids, lower-limb motor impairment scales, spasticity, recurrent stroke, prior rehabilitation exposure, and habitual physical activity was not available in the trial records. Smoking

status, hemoglobin concentration, diagnosed comorbidities (e.g., hypertension, coronary heart disease, and heart failure), medications (e.g., β-blockers), and resting heart rate were likewise not available. Height and body mass were measured, and body mass index (BMI) was calculated as body mass (kg) divided by height squared (m^2). BMI was categorized according to the Asia–Pacific criteria (<23, 23–24.9, and ≥25 kg/m^2, corresponding to normal weight, overweight, and obesity, respectively), which are recommended for Asian populations because cardiometabolic risk increases at lower BMI values than in European populations [26,27]. Resting systolic and diastolic blood pressure were obtained from the trial records. Balance was assessed with the BBS (0–56 points; higher scores indicate better balance), walking capacity with the 6 min walk test on an 18 m course, functional mobility with the TUG test (time to rise from a chair, walk 3 m, turn, return, and sit down), activities of daily living with the K-MBI (0–100 points), trunk control with the K-TIS (0–23 points), and isometric knee extension strength of the paretic leg with a rehabilitation dynamometer.

2.2. Cardiopulmonary Exercise Testing

Each participant performed a graded exercise test on a cycle ergometer with static wall fixation (Angio CPET, Lode B.V., Groningen, the Netherlands). CPET with respiratory gas analysis is the gold-standard test of cardiorespiratory fitness; it is objective, noninvasive, and widely used in clinical practice [11,13], and it has been reported to be safe and feasible in individuals with stroke [16,19]. Participants wore a face mask, and the gas analysis system (K4b2, COSMED, Rome, Italy) measured respiratory gases continuously on a breath-by-breath basis and stored them as 10 s averages. The K4b2 system has been validated against the Douglas bag method for measuring oxygen uptake over a wide range of exercise intensities [28]. Before each test, we calibrated the gas analyzers with ambient air and a reference gas and calibrated the flowmeter with a 3 L syringe, following the manufacturer's instructions.

After a 2 min warm-up at 0 W, the work rate was increased by 10 W every minute in a stepwise incremental protocol; participants were instructed to maintain a pedaling cadence of 60 rpm throughout the test. The test was terminated when participants could no longer continue because of fatigue or symptoms or could not maintain 60 rpm for ≥10 s (symptom-limited), in accordance with the ACSM termination criteria [22]. In accordance with these criteria, tests were terminated on the basis of participants' symptoms and pedaling cadence rather than gas-exchange variables. Heart rate telemetry linked to the gas analyzer yielded valid data in only 7 of the 45 tests; therefore, heart rate-based effort criteria were not applied. Details of seating adjustment, trunk support, foot fixation, assistance to the paretic limb, familiarization, and monitoring of blood pressure, oxygen saturation, and perceived exertion, as well as the reasons for test termination and adverse events, were not systematically documented in the records available for this analysis.

2.3. Derived Variables

All variables were recalculated from the 10 s averaged raw data using a uniform algorithm rather than device-generated values. Before analysis, 10 s intervals with implausible values indicating mask leakage or signal loss ($VO_2 \leq 50$ mL/min or $\dot{V}_E \leq 1$ L/min) were removed, and the one test stored breath by breath was averaged into consecutive 10 s bins. Cardiorespiratory fitness was evaluated as VO_2peak, defined as the highest 30 s (three consecutive 10 s intervals) rolling average (rolling averages were calculated only when all three intervals were present) and expressed in absolute (mL/min) and relative (mL/kg/min) terms; peak metabolic equivalents (METs) were calculated as VO_2peak divided by 3.5. Peak carbon dioxide output (VCO_2peak), peak minute ventilation ($\dot{V}_E$peak), respiratory exchange ratio (RER), respiratory rate, tidal volume, and end-tidal carbon dioxide pressure

were each determined independently as the highest 30 s rolling average and could therefore occur at a different time from VO_2peak; the dead space to tidal volume ratio was taken from the VO_2peak window. Peak work rate was defined operationally as the highest work rate sustained during the test and was calculated using the Kuipers equation to account for partially completed final stages in the stepwise protocol (Equation (1)) [29]:

$$W_{peak} = W_{completed} + (t/60) \times 10 \quad (1)$$

where $W_{completed}$ is the work rate (W) of the last completed stage and t is the time (s) spent in the final stage. Predicted VO_2max was calculated with the cycle ergometer equation of the Fitness Registry and the Importance of Exercise National Database (FRIEND) (Equation (2)) [30,31]:

$$VO_2max_{pred} = 45.2 - 0.35 \times age - 10.9 \times sex - 0.15 \times weight(lb) + 0.68 \times height(in) - 0.92 \quad (2)$$

where sex is coded as 1 for men and 2 for women, and the last term (0.46 × 2) is the cycle ergometer correction. To evaluate fitness relative to Koreans, sex-specific reference equations derived from 2646 healthy Korean adults were also applied (Equation (3)) [21]. Because these equations are based on treadmill testing, values were converted to cycle-equivalent values by dividing by 1.15, following the conversion used in the original study [21]:

$$VO_2max_{KR} = (50.54 - 0.26 \times age)/1.15 \text{ (men)}; (40.0 - 0.22 \times age)/1.15 \text{ (women)} \quad (3)$$

Ventilatory efficiency was assessed using the slope of the linear regression of $\dot{V}_E$ (L/min) on VCO_2 (L/min) during exercise ($\dot{V}_E/VCO_2$ slope) and the lowest 30 s average of $\dot{V}_E/VCO_2$ (nadir). OUES was calculated as the slope of the regression of VO_2 (mL/min) on $\log_{10}\dot{V}_E$ [15]. The increase in oxygen uptake relative to work rate ($\Delta VO_2/\Delta WR$) was calculated excluding the first minute of exercise to account for the delay in oxygen uptake kinetics [32]. Slope indices were derived only for tests with ≥60 s of exercise ($\dot{V}_E/VCO_2$ slope and OUES; one test was excluded), and $\Delta VO_2/\Delta WR$ only for tests with ≥3 completed work stages (n = 30). End-tidal carbon dioxide pressure ($P_{ET}CO_2$) was obtained during the first 30 s of exercise and at its peak, and the dead space to tidal volume ratio (V_D/V_T) at peak exercise.

The functional thresholds were as follows. A VO_2peak of 15 mL/kg/min, proposed in the literature as the minimum required for independent living in older adults [12], was used as a reference threshold for low aerobic fitness; it was not validated against functional independence in this cohort, and values below it indicate reduced aerobic fitness rather than demonstrated functional dependency. Sex-specific thresholds (18 mL/kg/min for men and 15 mL/kg/min for women) were applied in a sensitivity analysis [12]. Values <85% of predicted were defined as reduced cardiorespiratory fitness. A $\dot{V}_E/VCO_2$ slope of ≥34 was defined as ventilatory inefficiency [14], and a peak RER of ≥1.10 as attainment of maximal effort [13]. VO_2 estimated from work rate was calculated using the ACSM leg cycling equation (Equation (4)) [22]:

$$VO_2 \text{ (mL/kg/min)} = 1.8 \times (W \times 6.12)/\text{body mass (kg)} + 7 \quad (4)$$

Two tests in which the RER exceeded 1.10 during the first 30 s of exercise were flagged for possible hyperventilation or calibration problems. These tests were retained in the main analysis and excluded in a sensitivity analysis to examine the robustness of the results.

2.4. Statistical Analysis

Continuous variables are presented as mean ± standard deviation and median (interquartile range), and categorical variables as frequency (%) with Wilson 95% confidence intervals (CIs). Normality was assessed using the Shapiro–Wilk test. Sex differences were

compared using Welch's *t*-test or the Mann–Whitney *U* test, with Cohen's *d* as the effect size, and the Holm method was applied to correct for multiple comparisons across 21 CPET variables. Percent-predicted values based on the FRIEND and Korean references were compared using the Wilcoxon signed-rank test. Age groups (<50, 50–64, and ≥65 years) were compared using one-way analysis of variance when normality and homogeneity of variance (Levene's test) were satisfied and the Kruskal–Wallis test otherwise, followed by Bonferroni-corrected Mann–Whitney *U* tests; associations with age as a continuous variable were assessed using Spearman's correlation (ρ). Partial correlations adjusted for age and sex were used to examine associations between VO_2peak and other indices.

Factors associated with VO_2peak (mL/kg/min) were examined using multiple linear regression with age, sex, and body mass index (Model 1); these analyses were exploratory and describe statistical associations rather than independent biological determinants. A prediction equation was derived by adding peak work rate (Model 2). To examine stroke-specific correlates, BBS score, time since onset (log-transformed), stroke type, and side of hemiparesis were added to Model 1 using complete cases, and a final model retaining age, sex, and BBS score was fitted (Model 3). Regression assumptions were checked using variance inflation factors (VIFs), the Shapiro–Wilk test of residuals, the Breusch–Pagan test, and Cook's distance, and heteroscedasticity-robust (HC3) standard errors were also calculated. The prediction model was internally validated using the bootstrap optimism-corrected coefficient of determination (R^2; 1000 resamples) and the leave-one-out cross-validated root mean square error (RMSE). The two simplified equations (Equations (5) and (6)) were validated separately in the same manner; for Equation (6), the predicted absolute VO_2peak was divided by each participant's body mass so that R^2 and RMSE were calculated on the relative (mL/kg/min) scale.

The ability of peak work rate (W and W/kg) to identify a VO_2peak of <15 mL/kg/min was evaluated using the area under the receiver-operating characteristic (ROC) curve (AUC), with 95% CIs from 2000 bootstrap resamples; the optimal cut-off was determined using the Youden index [33]. Because the cut-off was selected and evaluated in the same sample, the entire selection procedure was internally validated: in each of 1000 bootstrap samples, the Youden-optimal cut-off was re-selected, and its sensitivity and specificity in the bootstrap sample were compared with those obtained by applying it to the original sample to estimate optimism; the distribution of re-selected cut-offs was summarized, and leave-one-out cross-validation was performed by re-selecting the cut-off without each participant and classifying that participant. Agreement between ACSM-estimated and measured VO_2peak was assessed using Bland–Altman analysis [34]; proportional bias was tested by regressing the differences in the means, and the intraclass correlation coefficient for absolute agreement ICC(2,1),was calculated [35]. The VO_2 response to work rate was analyzed using the average of the last 30 s of each stage completed for ≥40 s in a linear mixed-effects model with random intercepts and slopes. Stage-level ACSM estimates were calculated with each participant's body mass before averaging. Because fewer participants contributed at higher stages, the within-person difference between measured and ACSM-estimated VO_2 was also modeled against work rate (linear mixed-effects model with random intercepts), and the comparison was repeated in participants who reached ≥60 W.

Exploratory CPET-derived clusters were identified using k-means cluster analysis of five standardized variables (VO_2peak/kg, peak work rate, OUES/kg, $\dot{V}_E/VCO_2$ slope, and peak RER). The number of clusters (k = 2–5) was selected using the silhouette coefficient, robustness was examined against Ward's hierarchical clustering using the adjusted Rand index (ARI), and the results were visualized using principal component analysis. Between-cluster comparisons of the clustering variables are descriptive and were not used to validate

the clusters. Two-sided $p < 0.05$ was considered significant. Analyses were performed using Python 3.12 (SciPy 1.17, statsmodels 0.15, pingouin 0.7, and scikit-learn 1.8).

3. Results

3.1. Participant Characteristics

Of the 45 participants, 29 (64.4%) were men, and the mean age was 55.4 ± 12.0 years (range, 20–77 years). The mean body mass index was 24.9 ± 3.5 kg/m^2, and 40.0% had a body mass index of ≥25 kg/m^2. Men were taller and heavier than women, whereas age, age-group distribution, and body mass index did not differ by sex (Table 1). Of the participants with available clinical data, 24 had hemorrhagic stroke and 24 had left hemiparesis; the median time since onset was 24 months (interquartile range [IQR] 11–102; range 4–261), and the median BBS score was 49 (IQR 40–52). The median 6 min walk distance was 256.5 m (IQR 182.7–326.7), the TUG time was 15.2 s (10.4–18.4), the K-MBI score was 93 (88.8–97.0), and paretic knee extension strength was 14.0 kg (6.9–20.9). Resting systolic and diastolic blood pressure were 124.5 ± 13.1 and 79.9 ± 9.9 mmHg, respectively (n = 44), and 11 participants (25.0%) had values of ≥140/90 mmHg. These characteristics did not differ by sex.

Table 1. Characteristics of the participants.

Variable	Total (n = 45)	Men (n = 29)	Women (n = 16)	*p*
Age (years)	55.4 ± 12.0	54.3 ± 12.6	57.2 ± 11.1	0.438
<50 years, n (%)	15 (33.3)	11 (37.9)	4 (25.0)	0.645 †
50–64 years, n (%)	19 (42.2)	11 (37.9)	8 (50.0)	
≥65 years, n (%)	11 (24.4)	7 (24.1)	4 (25.0)	
Height (cm)	162.1 ± 7.5	165.8 ± 5.6	155.4 ± 5.7	<0.001
Body mass (kg)	65.4 ± 10.6	68.1 ± 10.2	60.5 ± 9.7	0.019
Body mass index (kg/m^2)	24.9 ± 3.5	24.7 ± 2.9	25.1 ± 4.4	0.725
BMI < 23, n (%)	10 (22.2)	5 (17.2)	5 (31.2)	0.541 †
BMI 23–24.9, n (%)	17 (37.8)	12 (41.4)	5 (31.2)	
BMI ≥ 25, n (%)	18 (40.0)	12 (41.4)	6 (37.5)	
Hemorrhagic/ischemic, n (%)	24 (54.5)/20 (45.5)	14 (50.0)/14 (50.0)	10 (62.5)/6 (37.5)	0.534 ¶
Right/left hemiparesis, n (%)	20 (45.5)/24 (54.5)	10 (35.7)/18 (64.3)	10 (62.5)/6 (37.5)	0.120 ¶
Time since onset (months)	24 (11–102)	24 (12–68)	23 (10–136)	0.779 ‡
BBS (score)	49 (40–52)	49 (42–52)	48 (39–51)	0.557 ‡
6 min walk distance (m)	256.5 (182.7–326.7)	267.3 (197.1–331.2)	197.1 (157.3–324.0)	0.228 ‡
TUG (s)	15.2 (10.4–18.4)	13.6 (9.7–17.7)	17.0 (12.4–22.1)	0.140 ‡
K-MBI (score)	93.0 (88.8–97.0)	94.0 (89.8–97.2)	93.0 (86.8–94.2)	0.230 ‡
K-TIS (score)	14.0 (11.8–16.0)	14.0 (11.8–15.2)	14.0 (12.5–16.2)	0.864 ‡
Paretic knee extension (kg)	14.0 (6.9–20.9)	15.6 (8.4–26.5)	11.7 (6.6–15.6)	0.107 ‡
Resting systolic blood pressure (mmHg)	124.5 ± 13.1	123.1 ± 13.8	126.9 ± 11.6	0.346
Resting diastolic blood pressure (mmHg)	79.9 ± 9.9	81.0 ± 9.4	77.9 ± 10.7	0.348
Blood pressure ≥ 140/90 mmHg, n (%)	11 (25.0)	7 (25.0)	4 (25.0)	1.000 ¶

Values are mean ± standard deviation or n (%). Continuous variables were compared using Welch's t-test. † χ^2 test across all categories. Body mass index categories follow the Asia–Pacific criteria [26,27]. Clinical data were missing for one male participant (6 min walk distance for two); resting blood pressure was available for 44 participants; percentages are based on participants with available data. Time since onset, BBS score, and the other clinical measures are presented as median (interquartile range). ‡ Mann–Whitney U test; ¶ Fisher's exact test. BBS, Berg Balance Scale; TUG, Timed Up and Go; K-MBI, Korean version of the Modified Barthel Index; K-TIS, Korean Trunk Impairment Scale.

3.2. Cardiopulmonary Exercise Testing Profile and Sex Differences

The median test duration was 320 s (5.3 min), and the peak work rate was 56.9 ± 26.8 W (0.87 ± 0.38 W/kg). VO_2peak was 1107 ± 436 mL/min and 16.8 ± 5.5 mL/kg/min (4.8 ± 1.6 METs), corresponding to 54.2 ± 19.2% of the FRIEND-predicted value and 57.8 ± 16.0% of the Korean reference value (Table 2). The Korean predicted value was on average 3.0 mL/kg/min lower than the FRIEND-predicted value, and the percent-predicted values differed significantly between the two references (Wilcoxon $p < 0.001$). The peak

RER was 1.01 ± 0.10; only 6 participants (13.3%) reached ≥1.10, and 24 (53.3%) reached ≥1.00. Because few participants met the maximal-effort criterion and 26 (57.8%) exercised for <6 min, VO_2peak in this study represents a symptom-limited peak value that may underestimate maximal cardiorespiratory capacity. The $\dot{V}_E/VCO_2$ slope was 30.8 ± 4.4, mostly within the normal range, and $\Delta VO_2/\Delta WR$ was 12.3 ± 2.8 mL/min/W.

Table 2. Cardiopulmonary exercise testing profile of individuals with stroke (N = 45).

Variable	n	Total, Mean ± SD	Median (IQR)	Men	Women	*p*	*d*	Holm *p*
Test duration (s)	45	342 ± 161	320 (220–450)	401 ± 158	234 ± 101	<0.001	1.18	0.002
Peak work rate (W)	45	56.9 ± 26.8	53.3 (36.7–75.0)	66.8 ± 26.3	39.0 ± 16.8	<0.001	1.19	0.002
Peak work rate (W/kg)	45	0.87 ± 0.38	0.85 (0.61–1.13)	0.98 ± 0.37	0.67 ± 0.32	0.006	0.88	0.082
VO_2peak (mL/min)	45	1107 ± 436	1075 (763–1404)	1236 ± 450	872 ± 296	0.002	0.90	0.035
VO_2peak (mL/kg/min)	45	16.8 ± 5.5	18.0 (12.8–19.7)	18.0 ± 5.6	14.5 ± 4.5	0.030 ‡	0.66	0.360
Peak METs	45	4.8 ± 1.6	5.1 (3.6–5.6)	5.1 ± 1.6	4.1 ± 1.3	0.030 ‡	0.66	0.360
VO_2peak, % predicted (FRIEND)	45	54.2 ± 19.2	50.9 (39.1–61.2)	49.7 ± 14.3	62.5 ± 24.1	0.066	−0.70	0.595
VO_2peak, % predicted (Korean)	45	57.8 ± 16.0	59.4 (42.4–69.0)	56.2 ± 14.8	60.8 ± 18.0	0.395	−0.29	1.000
VCO_2peak (mL/min)	45	1107 ± 467	1049 (728–1453)	1256 ± 487	839 ± 280	<0.001	0.98	0.012
$\dot{V}_E$peak (L/min)	45	39.0 ± 13.1	36.5 (29.2–48.6)	43.3 ± 13.3	31.2 ± 8.5	<0.001	1.02	0.011
Peak RER	45	1.01 ± 0.10	1.02 (0.95–1.06)	1.03 ± 0.06	0.99 ± 0.14	0.311	0.40	1.000
Peak respiratory rate (breaths/min)	45	31.4 ± 5.7	31.3 (29.1–33.3)	30.5 ± 5.5	33.1 ± 5.9	0.180 ‡	−0.46	1.000
Peak tidal volume (L)	45	1.33 ± 0.41	1.28 (1.06–1.58)	1.50 ± 0.38	1.01 ± 0.26	<0.001	1.44	<0.001
$\dot{V}_E/VCO_2$ slope	44	30.8 ± 4.4	30.6 (27.9–33.9)	30.9 ± 4.4	30.7 ± 4.5	0.930	0.03	1.000
$\dot{V}_E/VCO_2$ nadir	44	33.5 ± 4.7	32.8 (30.9–35.5)	33.0 ± 5.1	34.6 ± 3.9	0.249	−0.34	1.000
OUES	44	1868 ± 571	1795 (1450–2204)	2025 ± 580	1565 ± 421	0.005	0.87	0.070
OUES/kg	44	28.4 ± 7.3	27.9 (23.6–31.9)	29.6 ± 7.0	26.2 ± 7.6	0.158	0.48	1.000
$\Delta VO_2/\Delta WR$ (mL/min/W)	30	12.3 ± 2.8	12.6 (11.1–14.0)	12.4 ± 2.8	11.9 ± 3.2	0.690	0.18	1.000
$P_{ET}CO_2$ at exercise onset (mmHg)	45	34.7 ± 3.8	35.0 (32.7–36.3)	35.4 ± 4.0	33.3 ± 2.9	0.047	0.58	0.473
$P_{ET}CO_2$ peak (mmHg)	45	38.6 ± 3.5	38.7 (36.3–40.3)	39.2 ± 3.9	37.5 ± 2.6	0.082	0.50	0.657
VD/VT at peak	45	0.26 ± 0.05	0.25 (0.23–0.28)	0.27 ± 0.05	0.24 ± 0.04	0.019	0.73	0.245

p: Welch's *t*-test; ‡ Mann–Whitney *U* test (non-normal distribution). *d*: Cohen's *d* (men − women). Holm *p*: corrected for 21 variables. Predicted values were calculated using the FRIEND cycle equation [30] and the Korean reference equations converted to cycle-equivalent values [21]. Slope indices were derived from tests with ≥60 s of exercise (one test excluded), and $\Delta VO_2/\Delta WR$ from tests with ≥3 completed stages (n = 30). IQR, interquartile range; METs, metabolic equivalents; RER, respiratory exchange ratio; OUES, oxygen uptake efficiency slope; $P_{ET}CO_2$, end-tidal carbon dioxide pressure; V_D/V_T, dead space to tidal volume ratio.

Men had greater absolute exercise capacity than women, including peak work rate ($d = 1.19$), absolute VO_2peak ($d = 0.90$), $\dot{V}_E$peak ($d = 1.02$), and peak tidal volume ($d = 1.44$), and these differences remained significant after correction for multiple comparisons (Figure 1). Relative VO_2peak was higher in men (18.0 vs. 14.5 mL/kg/min, $p = 0.030$), but this difference was not significant after correction (Holm $p = 0.360$). Percent-predicted VO_2peak based on FRIEND tended to be higher in women (62.5% vs. 49.7%, $p = 0.066$), but this tendency disappeared when the Korean reference was applied (men, 56.2%; women, 60.8%; $p = 0.395$). The $\dot{V}_E/VCO_2$ slope, $\dot{V}_E/VCO_2$ nadir, OUES/kg, and $\Delta VO_2/\Delta WR$ did not differ by sex.

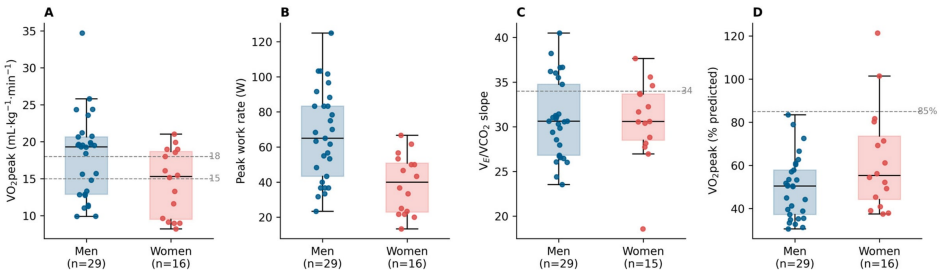

Figure 1. Distribution of key cardiopulmonary exercise testing indices by sex. (**A**) VO_2peak (dashed lines, 15 and 18 mL/kg/min); (**B**) peak work rate; (**C**) $\dot{V}_E/VCO_2$ slope (dashed line, 34); (**D**) VO_2peak as a percentage of the FRIEND-predicted value (dashed line, 85%). Boxes indicate medians and interquartile ranges, and dots indicate individual values.

3.3. Age-Related Differences and Factors Associated with Peak Oxygen Uptake

VO_2peak decreased stepwise across age groups (<50 years, 19.6; 50–64 years, 17.1; ≥65 years, 12.1 mL/kg/min; $p = 0.001$), and the ≥65-year group had significantly lower values than both younger groups (Table 3). Peak work rate, $\dot{V}_E$peak, and OUES showed the same pattern. Percent-predicted VO_2peak based on FRIEND did not differ across age groups ($p = 0.076$; $\rho = -0.18$), whereas with the Korean reference, the ≥65-year group (47.8%) had a significantly lower percentage than the 50–64-year group (61.9%; $p = 0.045$). Thus, compared with the Korean reference, in which the age-related decline is smaller, older individuals with stroke showed greater impairment not only in absolute but also in relative fitness (Figure 2). The $\dot{V}_E/VCO_2$ slope was positively correlated with age ($\rho = 0.40$), although the difference across age groups was not significant ($p = 0.067$). The proportion with a VO_2peak of <15 mL/kg/min was 81.8% in the ≥65-year group, markedly higher than in those aged <50 years (20.0%) and 50–64 years (26.3%; $p = 0.002$).

Table 3. Cardiopulmonary exercise testing indices by age group.

Variable	<50 Years (n = 15)	50–64 Years (n = 19)	≥65 Years (n = 11)	*p*	Post Hoc	Age ρ
Peak work rate (W)	74.0 ± 27.5	54.2 ± 24.3	38.2 ± 13.9	0.002	<50≠≥65	−0.56 ***
VO_2peak (mL/min)	1380 ± 451	1107 ± 374	735 ± 185	<0.001	50–64≠≥65, <50≠≥65	−0.59 ***
VO_2peak (mL/kg/min)	19.6 ± 6.2	17.1 ± 4.2	12.1 ± 3.2	0.001	50–64≠≥65, <50≠≥65	−0.54 ***
VO_2peak, % predicted (FRIEND)	52.9 ± 11.0	59.7 ± 22.4	46.5 ± 20.5	0.076 ‡		−0.18
VO_2peak, % predicted (Korean)	60.1 ± 15.1	61.9 ± 16.1	47.8 ± 13.6	0.045 ‡	50–64≠≥65	−0.22
$\dot{V}_E$peak (L/min)	45.4 ± 11.5	38.6 ± 14.3	30.8 ± 7.9	0.015	<50≠≥65	−0.49 ***
Peak RER	1.05 ± 0.08	0.97 ± 0.08	1.04 ± 0.12	0.036 ‡	50–64≠<50	−0.21
$\dot{V}_E/VCO_2$ slope	28.7 ± 2.8	32.0 ± 3.8	31.8 ± 6.1	0.067		0.40 **
OUES	2154 ± 568	1919 ± 532	1395 ± 306	0.002	50–64≠≥65, <50≠≥65	−0.52 ***
OUES/kg	30.8 ± 7.9	29.9 ± 6.4	23.0 ± 5.2	0.013	50–64≠≥65, <50≠≥65	−0.40 **
VO_2peak < 15, n (%)	3 (20.0)	5 (26.3)	9 (81.8)	0.002 §		

Values are mean ± standard deviation or n (%). *p*: one-way analysis of variance; ‡ Kruskal–Wallis test; § χ^2 test. Post hoc: pairs significant on Bonferroni-corrected Mann–Whitney *U* tests. ρ: Spearman's correlation with age as a continuous variable; ** $p < 0.01$, *** $p < 0.001$.

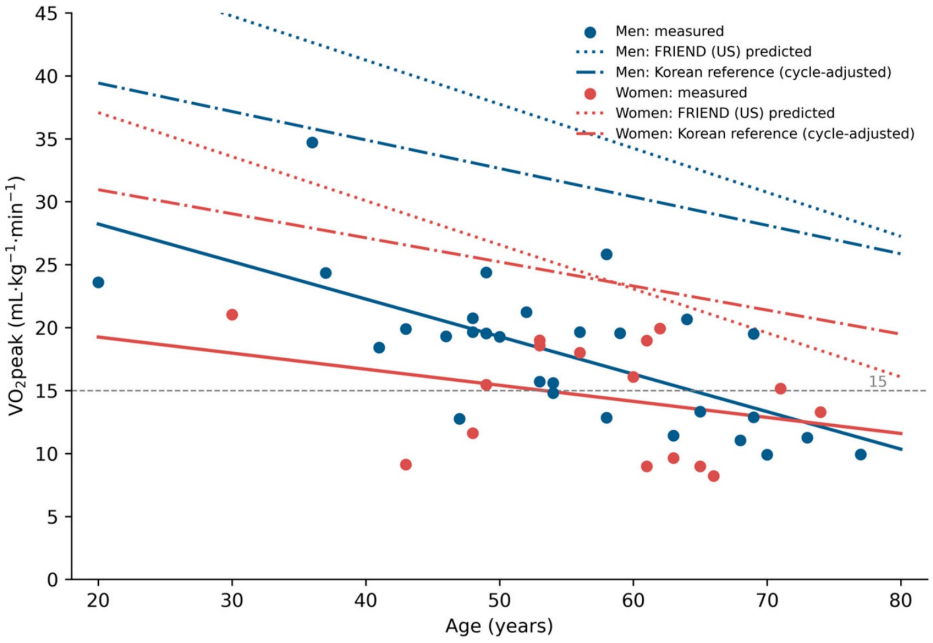

Figure 2. Measured VO_2peak and US-derived and Korean reference values by age. Dots and solid lines indicate measured values and sex-specific regression lines; dotted lines indicate FRIEND cycle-predicted values calculated using sex-specific mean body size; dash-dotted lines indicate Korean reference values converted to cycle-equivalent values [21]. The gray dashed line indicates 15 mL/kg/min.

In partial correlations adjusted for age and sex, VO_2peak was strongly associated with peak work rate (r = 0.80, 95% CI 0.66–0.89) and OUES (r = 0.65, 95% CI 0.43–0.80), but not with body mass index (r = 0.09, $p = 0.548$) or the $\dot{V}_E/VCO_2$ slope (r = −0.01, $p = 0.969$). In multiple regression (Model 1), age was most strongly associated with VO_2peak (standardized β = −0.54, $p < 0.001$), with VO_2peak decreasing by 0.25 mL/kg/min per year of age (Table 4). Male sex was associated with higher VO_2peak at a borderline level (β = 0.25, $p = 0.047$; HC3 $p = 0.061$), and body mass index was not significant. The three variables explained 39.5% of the variance in VO_2peak. All VIFs were ≤1.02, residual normality ($p = 0.46$) and homoscedasticity ($p = 0.51$) were satisfied, and the maximum Cook's distance was 0.26.

Table 4. Multiple linear regression analysis for VO_2peak (mL/kg/min).

Model	Variable	B (95% CI)	β	*p*
Model 1: associated factors	Intercept	25.71 (13.60 to 37.81)	—	<0.001
	Age (years)	−0.247 (−0.360 to −0.135)	−0.54	<0.001
	Sex (men = 1)	2.84 (0.04 to 5.64)	0.25	0.047
	Body mass index (kg/m^2)	0.116 (−0.271 to 0.504)	0.07	0.548
Model 2: prediction	Intercept	10.80 (2.60 to 19.00)	—	0.011
	Peak work rate (W)	0.181 (0.137 to 0.224)	0.88	<0.001
	Age (years)	−0.051 (−0.134 to 0.033)	−0.11	0.227
	Sex (men = 1)	−1.69 (−3.71 to 0.34)	−0.15	0.100
	Body mass index (kg/m^2)	−0.018 (−0.256 to 0.220)	−0.01	0.882
Model 3: clinical	Intercept	14.21 (3.67 to 24.75)	—	0.010
	Age (years)	−0.190 (−0.298 to −0.082)	−0.42	0.001
	Sex (men = 1)	2.62 (0.11 to 5.14)	0.24	0.042
	BBS (score)	0.247 (0.099 to 0.396)	0.39	0.002

B, unstandardized coefficient; β, standardized coefficient. Model 1: $R^2 = 0.395$, adjusted $R^2 = 0.350$, $F(3, 41) = 8.91$, $p < 0.001$. Model 2: $R^2 = 0.781$, adjusted $R^2 = 0.759$, $F(4, 40) = 35.68$, $p < 0.001$. For sex in Model 1, $p = 0.061$ with HC3 robust standard errors. Model 2 optimism-corrected $R^2 = 0.73$ (1000 bootstrap resamples); leave-one-out RMSE = 2.99 mL/kg/min. Model 3 (complete cases; one participant with missing clinical data excluded): $R^2 = 0.504$, adjusted $R^2 = 0.467$, $F(3, 40) = 13.58$, $p < 0.001$; all VIFs ≤ 1.10; for sex, $p = 0.052$ with HC3 robust standard errors. BBS, Berg Balance Scale.

Among the clinical characteristics, VO_2peak did not differ by stroke type (hemorrhagic, 16.5 ± 4.8; ischemic, 16.7 ± 6.2 mL/kg/min; $p = 0.908$) or side of hemiparesis (right, 15.2 ± 4.6; left, 17.7 ± 5.9 mL/kg/min; $p = 0.123$) and was not correlated with time since onset (ρ = 0.02, $p = 0.891$), whereas it was positively correlated with BBS score (ρ = 0.58, $p < 0.001$; partial ρ adjusted for age and sex = 0.49, $p = 0.001$). When BBS score, time since onset, stroke type, and side of hemiparesis were added to Model 1, only age and BBS score remained significant ($R^2 = 0.545$). In Model 3, age (β = −0.42, $p = 0.001$), BBS score (β = 0.39, $p = 0.002$), and male sex (β = 0.24, $p = 0.042$) together explained 50.4% of the variance in VO_2peak, 13.6 percentage points more than Model 1 fitted to the same participants (Table 4). Participants with a BBS score of ≤40 had lower VO_2peak than those with a score of >40 (12.9 ± 4.4 vs. 17.9 ± 5.2 mL/kg/min, $p = 0.008$), and 9 of 12 (75.0%) were below 15 mL/kg/min. Resting systolic and diastolic blood pressure were not associated with VO_2peak after adjustment for age and sex (partial r = 0.23, $p = 0.146$, and r = 0.12, $p = 0.443$, respectively), VO_2peak did not differ between participants with and without blood pressure of ≥140/90 mmHg (16.5 vs. 16.6 mL/kg/min, $p = 0.978$), and adding systolic blood pressure to Model 3 did not materially change the coefficients for age or BBS score (BBS, B = 0.241, $p = 0.002$).

In Model 2, which added peak work rate, only peak work rate was a significant predictor (β = 0.88), and age, sex, and body mass index were no longer significant. The model explained 78.1% of the variance (optimism-corrected $R^2 = 0.73$), with a standard error of the estimate of 2.69 and a cross-validated RMSE of 2.99 mL/kg/min. The simple prediction equation using peak work rate alone is given in Equation (5) ($R^2 = 0.751$; standard error

of the estimate, 2.77), and the equation for absolute VO_2peak in Equation (6) ($R^2 = 0.839$; standard error of the estimate, 179 mL/min):

$$VO_2\text{peak (mL/kg/min)} = 6.66 + 0.177 \times \text{peak work rate (W)} \quad (5)$$

$$VO_2\text{peak (mL/min)} = -471 + 12.12 \times \text{peak work rate (W)} + 13.59 \times \text{body mass (kg)} \quad (6)$$

When validated separately, Equation (5) had an optimism-corrected R^2 of 0.74 and a leave-one-out RMSE of 2.91 mL/kg/min. When the predictions of Equation (6) were divided by each participant's body mass, the relative-scale R^2 was 0.79 (optimism-corrected, 0.77) and the leave-one-out RMSE was 2.71 mL/kg/min. Across participants, the relative VO_2peak predicted by Equation (6) differed from that predicted by Equation (5) by −2.9 to +1.5 mL/kg/min, and the difference was inversely correlated with body mass ($r = -0.61$), indicating that the same absolute work rate corresponds to a lower relative VO_2peak in heavier individuals.

3.4. Functional Fitness Classification and Screening by Peak Work Rate

Overall, 37.8% of participants had a VO_2peak of <15 mL/kg/min, and 42.2% (men, 41.4%; women, 43.8%) fell below the sex-specific thresholds (18 mL/kg/min for men and 15 mL/kg/min for women) (Table 5). Peak METs were <5 in 48.9%, VO_2peak was <85% of predicted in 95.6% according to both references, and 25.0% had a $\dot{V}_E/VCO_2$ slope of ≥34. The proportion below 15 mL/kg/min did not differ by sex (34.5% vs. 43.8%, Fisher $p = 0.749$).

Table 5. Classification against published fitness thresholds and accuracy of peak work rate for identifying low capacity (N = 45).

Category	Criterion	n/N	% (95% CI)
Fitness thresholds	VO_2peak < 15 mL/kg/min	17/45	37.8 (25.1–52.4)
	VO_2peak < 18 mL/kg/min	22/45	48.9 (35.0–63.0)
	Below sex-specific threshold (men < 18, women < 15)	19/45	42.2 (29.0–56.7)
	Peak METs < 5	22/45	48.9 (35.0–63.0)
	<85% predicted: FRIEND/Korean	43/45/43/45	95.6/95.6
	<50% predicted: FRIEND/Korean	19/45/18/45	42.2/40.0
Ventilation and effort	$\dot{V}_E/VCO_2$ slope ≥ 34	11/44	25.0 (14.6–39.4)
	Peak RER ≥ 1.00	24/45	53.3 (39.1–67.1)
	Peak RER ≥ 1.10	6/45	13.3 (6.3–26.2)
	Test duration < 6 min	26/45	57.8 (43.3–71.0)
Screening accuracy (VO_2peak < 15)	Peak work rate, AUC	—	0.95 (0.87–1.00)
	≤48.3 W: apparent sensitivity/specificity	16/17/25/28	94.1/89.3
	≤48.3 W: apparent PPV/NPV	16/19/25/26	84.2/96.2
	≤48.3 W: optimism-corrected sensitivity/specificity	—	89.8/87.6
	Leave-one-out (cut-off re-selected): sensitivity/specificity	14/17/25/28	82.4/89.3
	Peak work rate per kg, AUC (cut-off ≤ 0.74 W/kg)	—	0.94 (0.85–1.00)

95% CIs for proportions were calculated using the Wilson method and those for AUCs from 2000 bootstrap resamples. Sex-specific thresholds follow Shephard [12]; the Korean reference follows Jang et al. [21]. The 15 mL/kg/min threshold is a published reference value and was not validated against functional independence in this cohort. Apparent accuracy values were derived and evaluated in the same sample; optimism-corrected values were obtained from 1000 bootstrap resamples in which the cut-off was re-selected. ≤48.3 W corresponds to failure to complete the 50 W stage. METs, metabolic equivalents; RER, respiratory exchange ratio; AUC, area under the curve; PPV, positive predictive value; NPV, negative predictive value.

Peak work rate showed excellent apparent discrimination for a VO_2peak of <15 mL/kg/min (AUC 0.95, 95% CI 0.87–1.00; Figure 3). At the Youden-optimal cut-off of ≤48.3 W, which in this protocol corresponds to failure to complete the 50 W stage (≤50 s at 50 W), the apparent sensitivity, specificity, positive predictive value, and negative predictive value were 94.1% (16/17), 89.3% (25/28), 84.2% (16/19), and 96.2% (25/26), respectively.

After internal validation that re-selected the cut-off in each bootstrap sample, the optimism-corrected sensitivity and specificity were 89.8% and 87.6%, respectively; the re-selected cut-off had a median of 48.3 W (IQR 43.3–48.3 W; 95% range 36.7–55.0 W). In leave-one-out cross-validation with re-selection of the cut-off, sensitivity was 82.4% (14/17) and specificity 89.3% (25/28). Peak work rate relative to body mass (cut-off ≤ 0.74 W/kg) showed similar discrimination (AUC 0.94, 95% CI 0.85–1.00).

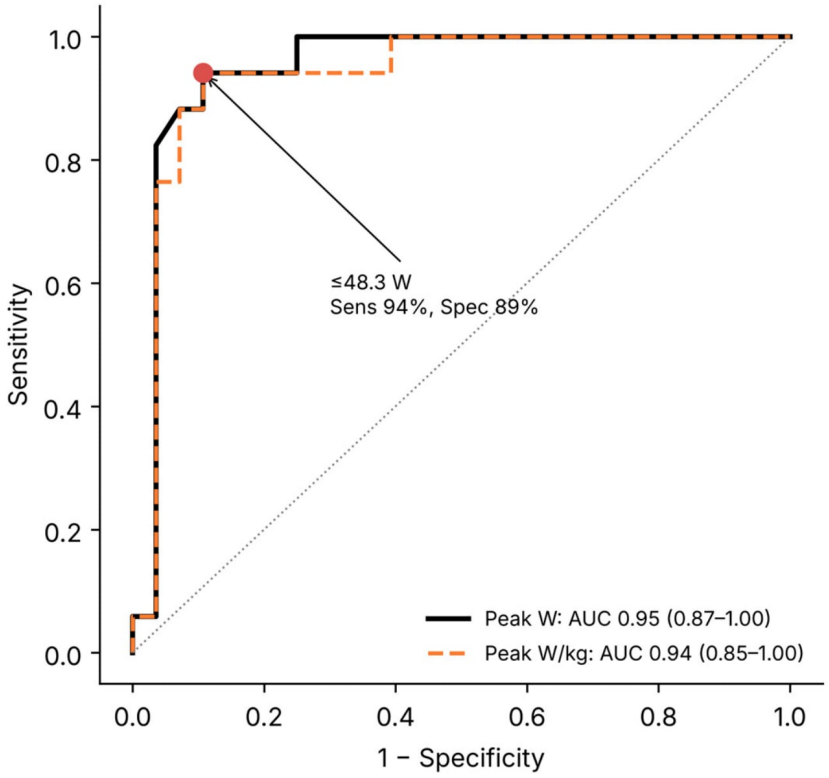

Figure 3. Receiver-operating characteristic curves of peak work rate (W) and peak work rate per body mass (W/kg) for identifying a VO_2peak of <15 mL/kg/min. The red dot indicates the Youden-optimal cut-off (≤48.3 W; apparent sensitivity 94.1%, specificity 89.3%).

3.5. Work Rate–Oxygen Uptake Relationship and Agreement of the ACSM Equation

In the linear mixed-effects model, the increase in VO_2 with work rate was 0.183 mL/kg/min/W (95% CI 0.172–0.195), with an intercept of 6.08 mL/kg/min (Figure 4A). At low work rates (10–40 W), measured VO_2 was 0.5–1.0 mL/kg/min lower than the ACSM estimate, whereas it was higher at ≥70 W. Within participants, the difference between measured and ACSM-estimated VO_2 increased by 0.20 mL/kg/min per 10 W ($p < 0.001$), and among the 21 participants who reached ≥60 W, the difference was −0.89, −0.34, and 0.00 mL/kg/min at 20, 40, and 60 W, respectively, indicating that the pattern was not explained solely by the change in the contributing sample at higher stages. In the Bland–Altman analysis, the mean bias between ACSM-estimated and measured VO_2peak was small (−0.17 mL/kg/min, 95% CI −1.00 to 0.67, $p = 0.688$), with 95% limits of agreement of −5.62 to 5.29 mL/kg/min (Figure 4B). However, proportional bias was significant (slope −0.28, $p = 0.001$): the ACSM equation overestimated VO_2peak by 1.63 ± 0.82 mL/kg/min in the lowest tertile and underestimated it by 2.08 ± 3.37 mL/kg/min in the highest tertile. The ICC(2,1) was 0.84 (95% CI 0.73–0.91), but only 60.0% of the estimates were within ±10% of the measured values.

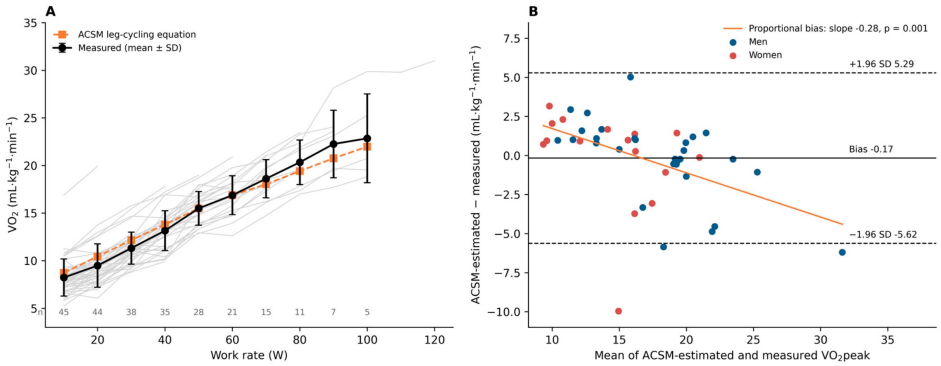

Figure 4. Work rate–oxygen uptake relationship and agreement of the ACSM equation. (**A**) VO_2 during the last 30 s of each stage. Gray lines indicate individuals, the black line indicates the mean ± standard deviation, and the orange dashed line indicates the mean of ACSM leg cycling estimates calculated with each participant's body mass; the numbers at the bottom indicate the participants who completed ≥40 s at each stage (stages with n ≥ 5 are shown). (**B**) Bland–Altman plot of ACSM-estimated versus measured VO_2peak. The solid line indicates the mean bias, the dashed lines indicate the 95% limits of agreement, and the orange line indicates the proportional-bias regression.

3.6. Exploratory CPET-Derived Clusters

In the k-means cluster analysis, the two-cluster solution had the highest silhouette coefficient (0.32; indicating limited separation), whereas the three-cluster solution separated only a single outlier. Agreement with Ward's hierarchical clustering was good (ARI 0.74). The first principal component (54.8% of variance) represented aerobic capacity, characterized by VO_2peak, peak work rate, and OUES/kg, and the second (24.9%) reflected RER and the $\dot{V}_E/VCO_2$ slope (Figure 5). Compared with the moderate-fitness cluster (n = 20), the low-fitness cluster (n = 24) was older (61.0 vs. 48.3 years), included more women (50.0% vs. 15.0%) and more individuals aged ≥65 years (41.7% vs. 5.0%), and had a higher $\dot{V}_E/VCO_2$ slope and lower peak RER (Table 6). Because these indices were clustering variables, their between-cluster differences are expected by construction and do not validate the clusters. All participants with a VO_2peak of <15 mL/kg/min belonged to the low-fitness cluster. The low-fitness cluster also had lower BBS scores than the moderate-fitness cluster (42.8 ± 9.2 vs. 50.2 ± 4.2, $p = 0.003$), whereas stroke type, side of hemiparesis, and time since onset did not differ.

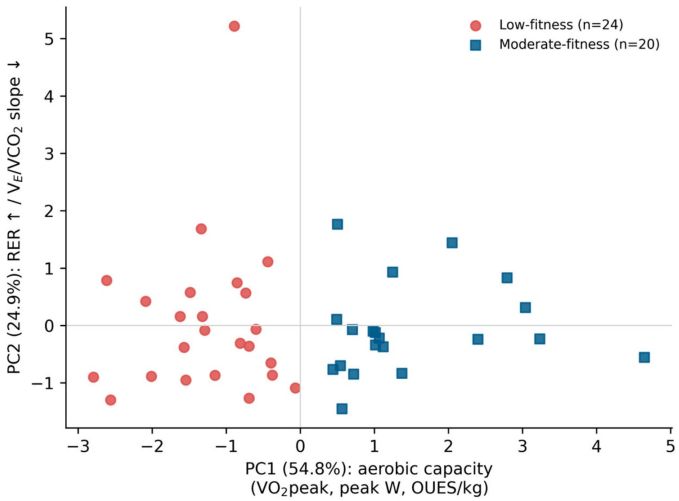

Figure 5. Two exploratory CPET-derived clusters shown in the principal component space of five indices. The first principal component reflects aerobic capacity, and the second reflects higher RER and lower $\dot{V}_E/VCO_2$ slope.

Table 6. Characteristics of exploratory CPET-derived clusters.

Variable	Low Fitness (n = 24)	Moderate Fitness (n = 20)	*p*
VO_2peak (mL/kg/min)	13.3 ± 3.4	21.3 ± 4.0	<0.001
Peak work rate (W)	39.4 ± 13.2	80.1 ± 19.8	<0.001
OUES/kg	23.6 ± 4.4	34.2 ± 5.7	<0.001
$\dot{V}_E/VCO_2$ slope	32.0 ± 4.7	29.3 ± 3.6	0.026
Peak RER	0.99 ± 0.10	1.05 ± 0.07	0.010
VO_2peak, % predicted (FRIEND)	50.1 ± 22.9	59.9 ± 12.2	0.005
Age (years)	61.0 ± 9.3	48.3 ± 11.7	<0.001
Body mass index (kg/m^2)	24.6 ± 3.7	25.1 ± 3.3	0.364
Women, n (%)	12 (50.0)	3 (15.0)	0.025 ¶
Aged ≥ 65 years, n (%)	10 (41.7)	1 (5.0)	0.006 ¶
VO_2peak < 15, n (%)	16 (66.7)	0 (0.0)	<0.001 ¶

Values are mean ± standard deviation or n (%). *p*: Mann–Whitney U test; ¶ Fisher's exact test. One participant whose $\dot{V}_E/VCO_2$ slope could not be derived was excluded from the cluster analysis. VO_2peak, peak work rate, OUES/kg, $\dot{V}_E/VCO_2$ slope, and peak RER were clustering variables; their comparisons are descriptive and do not constitute independent validation.

3.7. Sensitivity Analyses

Excluding the two flagged tests yielded nearly identical VO_2peak values (16.9 ± 5.4 mL/kg/min, n = 43) and regression coefficients (age, −0.239; sex, 2.62). When the analysis was restricted to the 24 participants who reached a peak RER of ≥1.00, VO_2peak was 18.6 ± 6.0 mL/kg/min and peak work rate was 69.4 W.

4. Discussion

This study comprehensively described the CPET profile, including ventilatory indices, of community-dwelling individuals with stroke in South Korea and, for the first time, compared it with Korean reference values. There were five main findings. First, VO_2peak was about half the predicted value according to both US-derived and Korean references, and four in ten participants fell below a published threshold proposed for independent living (15 mL/kg/min). Second, age and balance function were the main correlates of VO_2peak, and against the Korean reference, older individuals also showed greater relative impairment. Third, most participants terminated the test before reaching the maximal effort criterion, whereas ventilatory efficiency was relatively preserved. Fourth, a peak cycling work rate of ≤48.3 W (failure to complete the 50 W stage) identified low-fitness individuals with high apparent accuracy that remained good after internal validation of the cut-off selection, whereas the ACSM equation showed significant proportional bias. Fifth, an exploratory low-fitness cluster predominantly comprising older adults and women was identified.

The VO_2peak in this study (16.8 mL/kg/min) and its percentage of the predicted value (54%) fall within the range reported in a systematic review (8–22 mL/kg/min, or 26–87% of healthy controls) [5]. They are also similar to those of a North American chronic stroke cohort tested on a cycle ergometer [16] and to the baseline value of the exercise group in a randomized trial of community-dwelling individuals more than 6 months after stroke (18 ± 5 mL/kg/min) [20]. These findings confirm that cardiorespiratory fitness is markedly reduced in individuals with stroke in South Korea. More clinically important is that about half of the participants had peak METs of <5. Because daily activities such as brisk walking and stair climbing require 3–5 METs [22], these individuals use a large proportion of their maximal capacity for ordinary activities, which can lead to a vicious cycle of fatigue, activity avoidance, and further deconditioning [8,9].

The analysis using Korean reference values has important implications for clinical practice in Korea. Because the age-related decline in cardiorespiratory fitness is smaller in healthy Koreans than in Western populations, Western equations set relatively low predicted values for older Koreans [21]. Indeed, with the FRIEND reference, percent-predicted

VO_2peak did not differ across age groups and tended to be higher in women, whereas with the Korean reference, the sex difference disappeared and the relative impairment of those aged ≥65 years became evident. This suggests that relying solely on Western equations may underestimate the fitness loss of older individuals with stroke. In the same reference study, directly measured VO_2max values of Korean patients with coronary heart disease were 25.9 mL/kg/min in men in their 50s, 25.5 mL/kg/min in men in their 60s, and 22.3 mL/kg/min in women in their 60s [21]. When the values of our participants were converted to treadmill-equivalent values in the same manner (×1.15), they were 21.0, 17.0, and 14.9 mL/kg/min, respectively, lower even than those of patients with coronary heart disease, the primary target population of cardiac rehabilitation. Although the small number of participants in each age stratum warrants caution, this result suggests that individuals with stroke in Korea require systematic fitness assessment and exercise intervention comparable to or exceeding those provided in cardiac rehabilitation. However, the Korean reference values were estimated from treadmill performance rather than measured by gas analysis, and we applied a further conversion (÷1.15) to obtain cycle-equivalent values; comparisons with this reference should therefore be regarded as approximate.

Only 13.3% of participants reached the maximal effort criterion (RER ≥ 1.10), and the median test duration was 5.3 min. In contrast, the mean $\dot{V}_E/VCO_2$ slope was 30.8, with 75% of participants in the normal range, and it was not associated with VO_2peak after adjustment for age and sex. This suggests that many participants stopped exercising before reaching their cardiopulmonary limits, possibly because of motor impairment, fatigue of the paretic lower limb, or inability to maintain the required cadence. However, reasons for termination were not systematically recorded, and without measurements such as cardiac output or muscle oxygenation, the principal limiting factor cannot be determined. VO_2peak values in this study should therefore be interpreted as symptom-limited peak values that may underestimate maximal cardiorespiratory capacity, particularly in participants with short tests. A peripheral contribution would be consistent with reports of changes in muscle mass and fiber characteristics after stroke [6] and with the rapid increase in sarcopenia after onset reported in a review dominated by Asian patients [7]. It also agrees with a randomized trial in which training-induced improvements in VO_2peak were explained by an increase in the arteriovenous oxygen difference rather than cardiac output [20], and with the report that individuals with stroke are less likely than those with coronary artery disease to reach an intensity sufficient for exercise prescription [19]. In such settings, OUES, which depends less on maximal effort, may be a useful complementary index [14,15]; in this study, OUES was strongly correlated with VO_2peak after adjustment for age and sex ($r = 0.65$).

Balance function was the only stroke-specific characteristic associated with VO_2peak after adjustment for age and sex. Stroke type, side of hemiparesis, and time since onset were not related to VO_2peak, whereas each 10-point higher BBS score corresponded to an approximately 2.5 mL/kg/min higher VO_2peak, independent of age and sex. This is consistent with, but does not establish, a role of neuromuscular impairment, rather than the type or chronicity of stroke, in limiting exercise capacity in this population [6,20]. Moreover, three-quarters of participants with a BBS score of ≤40 were below the 15 mL/kg/min threshold, indicating that individuals with poor balance may warrant priority for fitness assessment.

Age was most strongly associated with VO_2peak, and 82% of those aged ≥65 years were below the threshold. Because the 15 mL/kg/min threshold is an absolute value, older individuals cross it first when stroke-related loss is added to age-related decline. Even in healthy individuals, VO_2max declines by about 5 mL/kg/min per decade [12], and as noted above, older individuals had greater relative impairment compared with the Korean reference. Older individuals with stroke therefore carry the double burden of aging and

stroke and may warrant priority for fitness assessment and intervention; whether their low aerobic fitness translates into functional dependency was not assessed in this study.

Sex differences were observed mainly in absolute body-size-related indices. Men had higher peak work rate, absolute VO_2peak, $\dot{V}_E$peak, and tidal volume, but the difference in relative VO_2peak was not significant after multiple-comparison correction. This is consistent with a chronic stroke study that found no sex difference in VO_2peak but greater ventilation and tidal volume in men [16]. Nevertheless, women had lower absolute fitness and were overrepresented in the exploratory low-fitness cluster; whether sex-specific assessment criteria are needed should be examined in larger samples.

A quarter of participants had a $\dot{V}_E/VCO_2$ slope of ≥34, and this index was positively correlated with age. In heart failure and cardiovascular disease, a high $\dot{V}_E/VCO_2$ slope predicts poor prognosis [14]. In individuals with stroke, ventilatory inefficiency may reflect comorbid cardiopulmonary disease or abnormal ventilatory control, so this subgroup may warrant further cardiovascular evaluation. The prognostic significance of this index in stroke remains unestablished.

The most practical contribution of this study is a preliminary criterion for identifying individuals with low fitness without gas analysis. Peak cycling work rate explained 75% of the variance in VO_2peak, and a cut-off of ≤48.3 W (failure to complete the 50 W stage) identified a VO_2peak of <15 mL/kg/min with an AUC of 0.95 and an apparent negative predictive value of 96.2%; that is, in this sample, individuals who completed the 50 W stage were unlikely to have a VO_2peak below this threshold. Because the cut-off was selected in the same sample, the optimism-corrected sensitivity (89.8%) and specificity (87.6%) are more realistic estimates, and the threshold should be regarded as preliminary until externally validated. It is also protocol-dependent: it was obtained with 10 W/min stages on a wall-fixed ergometer at 60 rpm, and work rate and VO_2peak were measured during the same symptom-limited test, so a gas-free assessment would need to reproduce the protocol, cadence requirement, and termination criteria. Moreover, an absolute work rate does not account for body size—48.3 W corresponds to 0.97 W/kg in a 50 kg individual but 0.60 W/kg in an 80 kg individual—and Equation (6) indicated that the same work rate corresponds to a lower relative VO_2peak in heavier individuals. After external validation, this criterion could serve as a simple screening indicator in community rehabilitation institutions, public health centers, and sports facilities for people with disabilities in Korea, where gas analyzers are rarely available. Given that concern about accidents during exercise is a main reason why Korean individuals with stroke avoid community exercise facilities [23], objectively confirming fitness with a simple cycle test and providing a safe exercise intensity may also help to increase facility use. In contrast, the ACSM equation was accurate at the group level but showed proportional bias, overestimating VO_2peak by approximately 1.6 mL/kg/min (approximately 0.5 MET) in those with the lowest fitness. If exercise intensity is set as a percentage of the estimated VO_2peak, the most vulnerable individuals may be prescribed a higher intensity than intended. This bias can be explained by the failure to reach a steady state at low work rates in the 1 min stage protocol and by the increased oxygen cost at higher work rates due to factors such as co-contraction; the within-person analysis showed that this pattern was not merely a consequence of fewer participants contributing at higher stages. Indeed, $\Delta VO_2/\Delta WR$ (12.3 mL/min/W) was higher than the commonly reported value of approximately 10 mL/min/W [32]. The stroke-specific prediction equations derived in this study (optimism-corrected R^2 0.74–0.77) could complement the ACSM equation in practice after external validation.

The exploratory cluster analysis suggested two groupings with limited separation. All participants below the threshold belonged to the low-fitness cluster, which had a higher proportion of older adults and women and a higher $\dot{V}_E/VCO_2$ slope. Because treatment

responses and training tolerance were not evaluated, these clusters should not be used to assign specific exercise prescriptions; whether such groups differ in their response to training requires prospective testing. Existing evidence indicates that combined aerobic and resistance training improves both cardiorespiratory fitness and muscle strength after stroke [36], that high-intensity walking training is effective in chronic stroke [37], and that aerobic and mixed training improve VO_2peak by 3.16 mL/kg/min on average, with moderate-to-high-intensity sessions of 45 min, three times per week for at least 8 weeks recommended [38,39].

This study has several strengths. CPET was directly measured in individuals with stroke, and all indices were recalculated from raw data using a standardized algorithm rather than device-generated values. Multiple aspects were analyzed, including ventilatory efficiency, OUES, functional thresholds, screening accuracy, equation validity, exploratory clusters, and comparison with Korean reference values, and the robustness of the results was confirmed with internal validation and sensitivity analyses.

This study also has limitations. First, the sample of 45 participants from a single program limits generalization to all individuals with stroke in Korea. Second, stroke severity was characterized by balance, walking, trunk function, daily living, and paretic knee strength. Motor impairment scales, spasticity, use of walking aids, comorbidities, medications, and habitual physical activity were not available, nor were smoking status, hemoglobin concentration, β-blocker use, and resting heart rate, which can influence VO_2peak and heart rate responses; these factors could therefore not be examined as potential confounders, although resting blood pressure was not associated with VO_2peak. Third, the 1 min stage protocol did not allow a steady state at low work rates, and because many tests were short, most participants' ventilatory threshold could not be reliably determined; furthermore, few participants met the maximal-effort criterion, valid heart rate data were available for only 7 tests, and test positioning, monitoring, reasons for termination, and adverse events were not systematically documented, so VO_2peak represents a symptom-limited value whose limiting factors could not be identified. Fourth, the Korean reference values were estimated from treadmill performance rather than measured by gas analysis and were further converted to cycle-equivalent values ($\div 1.15$) and may therefore contain error, and the threshold for independent living was derived from data on older adults and was not validated against functional independence in this cohort; actual independence in daily living and subsequent dependency were not assessed; cycle-based CPET reference values for Korean adults are needed. Fifth, the screening cut-off was derived and evaluated in the same sample; although internal validation that re-selected the cut-off reduced optimism, the cut-off is protocol-dependent and requires external validation. Sixth, the regression and cluster analyses were exploratory, and the cluster-based groupings were not tested against treatment response or outcomes. Finally, the cross-sectional design precludes causal inference. Future multicenter studies in Korean cohorts of individuals with stroke, including clinical information and standardized ramp protocols in accordance with guidelines [13,17], are needed to externally validate the screening criterion and prediction equation proposed here.

5. Conclusions

The cardiorespiratory fitness of community-dwelling individuals with stroke in South Korea is approximately half of the predicted value according to both US-derived and Korean references, and four in ten fall below a published aerobic fitness threshold proposed for independent living. Age and balance function, but not stroke type or time since onset, were associated with VO_2peak. Low aerobic fitness was concentrated among those aged $\geq$65 years, and using only Western equations may underestimate the relative impairment of older individuals. Most participants stopped before reaching the maximal effort crite-

rion, while ventilatory efficiency remained relatively preserved; thus, the measured values represent symptom-limited peak capacity. A peak cycling work rate of ≤48.3 W (failure to complete the 50 W stage) is a promising but preliminary, protocol-dependent criterion for identifying individuals with low fitness without gas analysis, whereas the ACSM equation overestimates fitness in those with low capacity and should be used with caution for exercise prescription. These findings provide a basis for community-based fitness assessment in individuals with stroke in Korea; the screening criterion and prediction equations require external validation, and the implications for functional independence and training response remain to be tested.

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Abbreviations

ACSM	American College of Sports Medicine
AUC	area under the curve
BBS	Berg Balance Scale
CI	confidence interval
CPET	cardiopulmonary exercise testing
FRIEND	Fitness Registry and the Importance of Exercise National Database
ICC	intraclass correlation coefficient
METs	metabolic equivalents
OUES	oxygen uptake efficiency slope
$P_{ET}CO_2$	end-tidal carbon dioxide pressure
RER	respiratory exchange ratio
RMSE	root mean square error
ROC	receiver-operating characteristic
V_D/V_T	dead space to tidal volume ratio
$\dot{V}_E$	minute ventilation
VCO_2	carbon dioxide output
VO_2peak	peak oxygen uptake
$\Delta VO_2/\Delta WR$	increase in oxygen uptake relative to work rate

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