Estimating Cardiorespiratory Fitness in Well-Functioning Older Adults: Treadmill Validation of the Long Distance Corridor Walk

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OBJECTIVES: To determine criterion validity of the 400-m walk component of the Long Distance Corridor Walk (LDCW) and develop equations for estimating peak oxygen consumption (VO_2) from 400-m time and factors intrinsic to test performance (e.g., heart rate (HR) and systolic blood pressure (SBP) response) in older adults.

DESIGN: Cross-sectional validation study.

SETTING: Gerontology Research Center, National Institute on Aging, Baltimore, Maryland.

PARTICIPANTS: Healthy volunteers (56 men and 46 women) aged 60 to 91 participating in the Baltimore Longitudinal Study of Aging between August 1999 and July 2000.

MEASUREMENTS: The LDCW, consisting of a 2-minute walk followed immediately by a 400-m walk "done as quickly as possible" over a 20-m course was administered the day after maximal treadmill testing. HR and SBP were measured before testing and at the end of the 400-m walk. Weight, height, activity level, perceived effort, and stride length were also acquired.

RESULTS: Peak VO_2 ranged from 12.2 to 31.1 mL oxygen/kg per minute, and 400-m time ranged from 2 minutes 52 seconds to 6 minutes 18 seconds. Correlation between 400-m time and peak VO_2 was -0.79. The estimating equation from linear regression included 400-m time (partial coefficient of determination (R^2) = 0.625), long versus short stride (partial $R^2 = 0.090$), ending SBP (partial $R^2 = 0.019$), and a correction factor for fast 400-m time (<240 seconds; partial $R^2 = 0.020$) and explained 75.5% of the variance in peak VO_2 (correlation coefficient = 0.87).

CONCLUSION: A 400-m walk performed as part of the LDCW provides a valid estimate of peak VO_2 in older adults. Incorporating low-cost, safe assessments of fitness in clinical and research settings can identify early evidence of physical decline and individuals who may benefit from therapeutic interventions. **J Am Geriatr Soc 54:127–132, 2006.**

Key words: aerobic fitness testing; validation; walking test; aged

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Assessment of cardiorespiratory fitness provides important objective information on the capacity of older adults to perform essential and desired activities.[1–3] Because substantial decline in exercise tolerance may precede recognition of mobility-related difficulty, particularly in sedentary older people,[4,5] fitness assessment may also serve as an early indicator of impending functional limitation in clinical practice and for research purposes.

The impracticality of maximal and submaximal treadmill-based walking tests for assessment of cardiorespiratory fitness in older adults, especially those aged 75 and older, is well recognized.[6–10] A variety of self-paced walking test protocols have been developed[10–15] as alternative approaches to fitness assessment and estimation of peak oxygen consumption (VO_2), yet few data exist on the relationship between self-paced and treadmill-based walking test performance applicable to healthy older adults. Equations for estimating peak or maximal VO_2 from self-paced walking tests have been developed, but either the walking distance was exceptionally long (e.g., 1 mile) and the population devoid of older adults,[12,13,15] or the walk was brief and time-based (e.g., 5 minutes) and was evaluated primarily in persons with debilitating conditions.[14,16,17]

To overcome deficiencies of existing measures of exercise tolerance, a three-component, two-stage, self-paced walking test, the Long Distance Corridor Walk (LDCW), was developed.[10] Key features include a 2-minute warm-up walk, in which the first 20 m is timed and full and partial steps are manually counted. The first stage also serves as a stepped-down test for debilitated persons unable to walk for a longer period. The second stage focuses on distance

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(400 m) instead of time (e.g., 6 minutes). Previously, it was demonstrated that older adults perform closer to capacity when given a specific distance to walk, such as 400 m, than when given a specific length of time, such as 6 minutes.[10] This report provides objective validation of the 400-m walk component of the LDCW by comparing it with the criterion standard for aerobic fitness: maximal treadmill testing with measured VO_2. In addition, an estimating equation for peak VO_2 was developed using time to walk 400 m "as quickly as possible" and other factors related to test performance, such as heart rate (HR) and systolic blood pressure (SBP), as necessary to improve model fit.

METHODS

Study Population

The study population consisted of 102 consecutive participants, 56 men and 46 women, in the Baltimore Longitudinal Study of Aging (BLSA) aged 60 to 91 who were seen between August 1999 and July 2000 and had a valid maximal treadmill test, with measured VO_2. All subjects signed a separate consent form to participate in the "Treadmill Validation of the Health ABC Long-Distance Corridor Walk" approved by the Johns Hopkins Bayview Medical Center institutional review board for human research. Subjects were administered the LDCW as part of their regular BLSA visit the day after they underwent a maximal treadmill walking test. Use of antihypertensive agents, including beta-blockers, was not a study exclusion, but only two participants, one man and one woman, were taking beta-blockers at the time of testing.

Treadmill-Based Measurement of Cardiorespiratory Fitness

After providing written informed consent, BLSA participants with no clinically significant cardiovascular disease or orthopedic or neuromuscular limitations underwent a symptom-limited maximal treadmill test followed a modified Balke protocol with measurement of VO_2.[18] In brief, men walked at 3.5 miles/hr and women at 3.0 miles/hr with treadmill grade increased 3% every 2 minutes until voluntary exhaustion. Expired gas volumes were measured using a Parkinson-Cowan gas meter. Expired oxygen (O_2) and carbon dioxide concentrations were measured using a medical mass spectrometer (Perkin-Elmer MGA-1110, Boston, MA). O_2 consumption was measured continuously and averaged every 30 seconds throughout exercise, and the highest value was termed peak VO_2, expressed as mL O_2/kg per minute. Heart rate and brachial artery cuff pressure were obtained before exercise and at the end of each 2-minute stage. For the present study, only individuals who appeared to achieve maximal effort, as defined by a peak HR of 85% of age-predicted maximum and the assessment of the supervising physician (JLF), underwent the LDCW.

LDCW Administration

The LDCW course was 20 m and marked by traffic cones at both ends. Before testing, a portable HR monitor was placed on the subject, and pretest HR was recorded (Polar Pacer, Model 61190, Polar Electro, Oy, Finland). For the 2-minute walk, subjects were instructed to walk down the corridor, around the traffic cone, and back, in a continuous fashion, covering as much ground as they could in 2 minutes. Standard encouragement was given each lap and subjects were also told, "You have 30 seconds to go," "10 seconds to go," and "Stop. Stay where you are." Ending HR, Borg perceived exertion rating,[19] time, and a manual count of full and partial steps taken for the first 20 m and laps and meters completed were recorded. Within 30 seconds of completion, subjects were brought back to the start for the 400-m walk and instructed to complete 10 laps "as quickly as possible." At the end of each lap, standard encouragement was given, as well as laps remaining (e.g., "4 down, 6 to go"). Seconds to complete 400 m, ending HR and SBP, and Borg perceived exertion rating[19] were recorded. For safety purposes, the examiner was instructed to stop subjects during either walk if their HR exceeded 170 beats per minute or they reported chest or leg pain, dyspnea, dizziness, feeling faint, or other significant symptoms. None of the study subjects needed to stop the LDCW prematurely.

Other Measures

Height in centimeters and weight in kilograms were determined on a standard physician's stadiometer and balance scale, respectively. Usual self-reported vigorous physical activity level was coded from 0 to 3, corresponding to activity levels of none, low ($<$20 min/wk), moderate (20–59 min/wk), and high ($\geq$60 min/wk). Stride length was determined from the number of steps needed to cover the first 20 meters of the 2-minute walk.

Statistical Analysis

Overall and sex-specific associations between 400-m time and peak VO_2 were examined using Pearson correlation coefficients. To develop the most precise, yet simplified, equations for estimating peak VO_2 from 400-m time, variables intrinsic to performance on the LDCW were systematically added to a multiple linear regression model with seconds to walk 400 m as the primary independent variable and measured peak VO_2 as the dependent variable. To capture exertion-related factors, Borg perceived effort rating,[19] ending SBP, percentage change in HR from just before LDCW administration to the end of the 400-m walk, and ending HR were examined. Stride length was considered after observing that persons with a long stride typically altered their steps to negotiate the turns at each end of the LDCW course. The Borg scale and stride length were examined as continuous and dichotomous variables with cutpoints determined from systematic evaluation of the value that contributed most to the explained variance (produced the largest coefficient of determination (R^2)). Variables were included in the final model if they made a significant independent contribution ($P<.05$) to the explained variance in measured peak VO_2.

After finalizing the predictive model using variables intrinsic to the LDCW, the added contribution of several characteristics typically associated with aerobic performance, including height, weight, body mass index (BMI), age, sex, race, treadmill testing experience (first BLSA visit or not), and physical activity level to the prediction of measured peak VO_2 was examined.

Table 1. Sample Characteristics and Response to Fitness Testing

Characteristic	Total (N = 102)	Men (n = 56)	Women (n = 46)
Black, n (%)	26 (25)	9 (16)	17 (37)
First Baltimore Longitudinal Study of Aging visit, n (%)	33 (32)	18 (32)	15 (33)
Physically active ($\geq$20 min/wk), n (%)	35 (34)	19 (34)	16 (35)
Long stride length (<1.2 steps/m) n (%)	49 (48)	41 (73)	8 (17)*
Perceived hard effort (Borg $\geq$15/20), n (%)	49 (48)	34 (61)	15 (33)*
Age (mean $\pm$ SD)	71.6 (7.8)	72.1 (7.6)	70.9 (8.1)
Body mass index, kg/m^2 (mean $\pm$ SD)	26.9 (3.7)	27.7 (3.1)	26.0 (4.2)
Ending heart rate, beats/min (mean $\pm$ SD)	123 (19.2)	122 (19.2)	124 (19.4)
Ending systolic blood pressure, mmHg (mean $\pm$ SD)	174 (24.2)	179 (23.8)	169 (23.7)
Seconds to walk 400 m (mean $\pm$ SD)	255 (40.9)	244 (38.1)	269 (40.3)*
Peak oxygen uptake, mL oxygen/kg per minute (mean $\pm$ SD)	22.2 (4.4)	23.7 (4.0)	20.3 (4.1)*

* $P<.01$ for difference between men and women.
SD = standard deviation.

RESULTS

Table 1 summarizes study participant characteristics and aspects of the testing experience. The mean age was 72, one quarter of the sample was black, just over one third engaged in moderate to heavy physical activity, and one third was new BLSA participants. Measured peak VO_2 ranged from 12.2 to 31.1 mL O_2/kg per minute, with a mean of 22.2, and 400-m time ranged from 2 minutes 52 seconds to 6 minutes 18 seconds, with a mean of 4 minutes 15 seconds. Women, on average, had a lower measured peak VO_2 ($P<.001$), needed more time to walk 400 m ($P=.002$), were less likely to report an effort level of at least 15 out of 20 on the Borg scale for the LDCW ($P=.009$), and were less likely to have a long stride (<1.2 steps/m; $P<.001$) than men. Nevertheless, the raw correlations between 400-m time and measured peak VO_2 were similarly high for men and women: -0.75 and -0.78, respectively, and -0.79, overall. Figure 1A shows measured peak VO_2 plotted against seconds to walk 400 m.

Few factors other than 400-m time contributed to the explained variance in measured peak VO_2. Borg perceived effort rating during the 400-m walk made no contribution whether included as a continuous ($P=.499$) or a dichotomous variable ($P=.86$). Of the HR response measures examined, only ending HR approached a significant first-order contribution ($P=.08$), which diminished ($P=.26$) when ending SBP ($P=.01$) was included in the model. Stride length proved to be an important adjustment factor whether used as a continuous variable (steps over 20 m) or as a dichotomous measure of long versus short stride (<1.2 steps/m) ($P<.001$ for both). Because the R^2 associated with the dichotomous measure was larger than that associated with total steps (0.091 vs 0.059), a simple indicator variable for long stride (1 = yes, 0 = no) was used in the final model.

The estimating equation following the original planned approach included three variables: seconds to walk 400 m, long versus short stride, and ending SBP. From the scatterplot of estimated versus measured values of peak VO_2, it appeared that the equation consistently underestimated peak VO_2 in persons with high measured peak VO_2. Thus, to further improve the fit of the estimating equation, the presence of an inflection point where the relationship between 400-m time and measured peak VO_2 departed from linearity was tested for. A significant point of departure was found at 240 seconds ($P=.006$). Thus, if 400-m time was 240 seconds or slower, the correction factor (CF) was 0. If time was faster than 240 seconds, the CF was 400-m time minus 240, times the parameter estimate of -0.064 ($P=.006$). A quadratic function was also examined but performed no better than the simple linear equation with the correction factor. Thus, the final equation for estimating peak VO_2 from the 400-m walk component of the LDCW was:

$$39.431-(0.054\times 400\text{-m seconds})+(2.832\times \text{long stride})$$
$$-(0.031\times \text{ending SBP})-(0.064\times \text{CF})$$

This equation explains 75.5% of the variance in measured peak VO_2, an absolute increase of 13.0%, or 20.8% improvement over that explained by 400-m time alone (62.5%). Further detail and an alternative equation using ending HR in place of ending SBP with a similarly high R^2 can be found in Table 2. The plot of estimated versus measured values of peak VO_2 is shown in Figure 1B, with a Bland-Altman plot of measurement agreement (inset[20]).

To determine whether the model could be further improved, characteristics frequently associated with fitness test performance were examined individually for their potential to explain any additional variance in measured peak VO_2. No attributes examined—age, sex, race, BMI, height, activity level, or new BLSA participant status—significantly improved estimation of peak VO_2 (data available on request).

DISCUSSION

This study demonstrates that performance on the 400-m walk component of the LDCW is a valid indicator of aerobic capacity in men and women aged 60 and older free of overt cardiovascular disease and mobility limitations. Adjusting for a few key variables that distinguish self-paced corridor walking over a 20-m course from a graded treadmill-based protocol improved the estimation of peak VO_2 21% over time to walk 400 m alone, increasing the explained variance from 62.5% to 75.5%. One adjustment

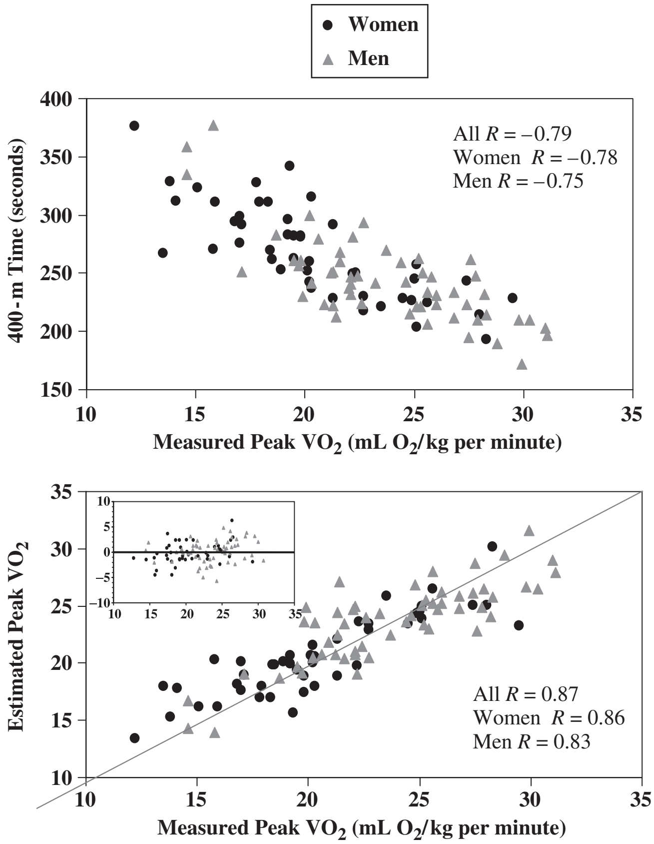

Figure 1. A. Plot of measured peak oxygen consumption (VO_2) in mL O_2/kg per minute by seconds to walk 400 m. B. Plot of measured peak VO_2 in mL oxygen O_2/kg per minute by peak VO_2 estimated by the equation: 39.431 $-$(0.054 $\times$ 400-m seconds) $-$(0.031 $\times$ ending SBP)+(2.832 $\times$ long stride) $-$(0.064 $\times$ CF). 400-m seconds = 400-m time in seconds; ending SBP = systolic blood pressure taken within 60 seconds of completing the 400-m walk, long stride = 1 if stride length is $<$1.2 steps/m or $<$24 steps over 20 meters and 0 otherwise; CF = the correction factor, which equals 0 when 400-m time is $>$240 seconds and 240–400-m seconds when 400-m time = 240 seconds. The diagonal line represents the line of perfect agreement. The graph in the upper left-hand corner is the Bland-Altman plot of measurement agreement, in which the x-axis is the mean of measured and estimated VO_2 and the y-axis is the residual of measured minus estimated peak VO_2. The horizontal line at 0 represents perfect agreement. R = correlation coefficient.

factor, long versus short stride length, likely accounts for the reduced walking efficiency of persons with longer strides in negotiating the 19 turns around traffic cones on the 20-m course. A second adjustment, ending SBP, probably reflects individual variation in exertion. Finally, the nonlinear correction factor, which effectively up-weights exceptionally fast walk times ($<$240 seconds, or faster than 3.75 mph), reflects the limitations of walking at 0 grade for discriminating cardiorespiratory fitness levels much above 28 mL O_2/kg per minute. Because less than 20% of persons aged 60 and older and very few aged 75 and older have a peak VO_2 greater than 28 mL O_2/kg per minute,[6,21] the LDCW appears to be a valid tool for evaluating cardiorespiratory fitness for a majority of older adults, particularly when the estimating equation is applied.

Table 2. Final Model for Estimating Peak Oxygen Uptake (VO_2)

Variable	Parameter Estimate	P-value	Partial R^2
Intercept	39.431	$<$.001	
Seconds to walk 400 m	$-$0.054	$<$.001	0.625
Long stride length ($<$1.2 steps/m)	2.832	$<$.001	0.090
Ending systolic blood pressure, mmHg	$-$0.031	.01	0.019
Nonlinear CF*	$-$0.064	.006	0.020

Note: Alternative model using ending heart rate (non-beta-blocker users only): Estimated peak VO_2 = 40.133 $-$ (0.059 $\times$ 400-m seconds)+(2.601 $\times$ long stride) $-$ (0.039 $\times$ ending HR) $-$ (0.071 $\times$ CF); model coefficient of determination (R^2 = 0.75).

* If time to walk 400 m was $\geq$240 seconds, then the correction factor (CF) was zero. If time was $<$240 seconds, then the CF was seconds to walk 400 m $-$ 240.

The equation developed in this study provides an estimate of peak VO_2 comparable with those from previous studies estimating peak or maximal VO_2 from performance on self-paced walking tests.[12–15,22] Even though the prediction factors differed, most reported R^2s of approximately 0.76,[13,14,22] as was found here, with a range from 0.58[15] to 0.86.[12] Differences reflect variation in the reference populations, course length, covariates examined, and model building approaches. Other studies included younger participants over a broader age range (e.g., 20–64) and used longer walking courses, ranging from 0.5 miles to 2 km.[12,13,15,22] None considered stride length or evaluated the assumption of linearity across the full range of fitness tested. Although three[12,13,22] of the four studies[15] that examined ending HR found it to be important, as was found here, none ascertained ending SBP, which was marginally superior to ending HR for increasing the explained variance in this study. All previously developed estimating equations included age and sex, unless sex-specific models were constructed[13] or only women were examined,[15] and at least one additional participant characteristic, such as BMI,[13,15] weight,[12,14] and activity level.[22] In this study, the contribution of participant attributes was considered only after variables intrinsic to the LDCW were evaluated. Using this approach, none of the participant characteristics produced a significant increase in the explained variance in measured peak VO_2 (data available on request).

The 400-m walk performed as part of the LDCW appears to provide a superior estimate of peak VO_2 than other commonly used approaches in older adults. The raw correlation of $-$0.79 between 400-m time and measured peak VO_2 substantially exceeds the magnitude of association found in studies relating 6-minute-walk distance to peak or maximal VO_2, with correlations ranging from 0.45 in healthy older adults with peak VO_2 greater than 18 mL O_2/kg per minute[23] to 0.52 to 0.59 in older patients with heart failure[16,24] and lung disease[17] and up to 0.64 in less-fit (VO_2 $<$18 mL O_2/kg per minute)[23] and other community-resident elderly.[6,25] Additionally, the raw correlation between 400-m time and measured peak VO_2 ($-$0.79) is comparable with the correlations (0.70–0.75) found between measured VO_2 and that generated by equations commonly used to predict maximal VO_2 in lieu of direct measurement of O_2 consumption during treadmill testing.[26]

The United States Social Security Administration (SSA) has identified a peak VO_2 below 18.0 mL O_2/kg per minute as indicating disability,[27] and several empirical studies of older adults have found similar threshold values for independent living.[3–5,21] Substituting the study population mean value for ending SBP (174 mmHg) in the estimating equation and using the SSA criteria equates to a 400-m time of 4 minutes 57 seconds for short stride and 5 minutes 49 seconds for long stride. Applying Astrand's estimate of 12 mL O_2/kg per minute as the minimum requirement for walking across a street[5] translates to a 400-m time ranging from 6 minutes 48 seconds to 7 minutes 40 seconds. To the degree that 12 to 18 mL O_2/kg per minute represents minimal to suboptimal fitness levels for independent functioning in the community, these analyses suggest that persons aged 60 and older unable to cover 400 m, walking as quickly as possible, in less than 7 minutes may have significant functional limitations and that those slower than 5:30 may be at high risk of impending functional difficulty.

In the Study of Physical Performance and Age-Related Conditions in Sonomans (SPPARCS), only half of persons aged 70 to 79 and one quarter of those aged 80 and older met treadmill test inclusion criteria and were willing to undergo testing.[6] Of those, 83% and 80% of men aged 70 to 79 and 80 and older, respectively, had adequate performance, and 46% and 27% met maximal criteria. The respective percentages for women were much lower—67%, 46%, 25%, and 18%. Applying percentages of minimal performance to all enrollees in SPPARCS, only 40% of men and 33% of women aged 70 to 79 could provide fitness-related data using a treadmill-based protocol. Similarly, another study[5] found only 30% of women aged 75 and older were able to achieve maximal treadmill exercise criteria. In contrast, in the health, aging and body composition study, 80% of men and 72% of women aged 70 to 79 met eligibility criteria and completed all stages of the LDCW, including the 400-m walk.[28]

Some limitations of the current study should be recognized. Even though the LDCW was developed to provide more-complete ascertainment of cardiorespiratory fitness in older persons, particularly those excluded from treadmill-based tests, this validation study included only persons able to complete a symptom-limited graded treadmill walking test. Thus, one limitation is the unknown applicability of study findings and estimating equations to frailer yet ambulatory older adults. Nevertheless, an analysis of the 17 persons in the current sample who met SSA peak VO_2 criteria for disability (<18 mL O_2/kg per minute) found good agreement between measured and estimated peak VO_2, with a mean residual of -1.45 and a nonsignificant ($P = .33$) negative correlation (-0.25) between the residual and the mean of measured and estimated peak VO_2. The slightly higher estimate of aerobic capacity with 400-m time is consistent with the notion that treadmill walking is problematic for older persons with low fitness[8] and provides further support for use of self-paced corridor walks in aged individuals.

A second study limitation concerns the lack of a planned validation sample. Following the approach used in another study with a small sample,[15] in a post hoc analysis, an estimating equation derived using two thirds of the cohort (n = 68), selected by dropping every third person from a list sorted by BLSA identification number, was applied to the remaining one third (n = 34) of the sample. Although the equation differed slightly from the equation derived from the full sample, the same factors were identified, including the correction factor. The coefficient of determination (0.746) and correlation coefficient (0.86) for the two-thirds sample were nearly identical to those obtained using the full sample. For the one-third validation sample, the correlations between measured peak VO_2 and that estimated using the equation derived from the two-thirds sample were 0.88 overall and 0.83 and 0.87, respectively, for women and men.

In sum, the LDCW, which consists of 2-minute and 400-m walk components, represents a viable alternative to maximal treadmill tests for assessing cardiorespiratory fitness, a critical dimension of health and functional status, in older adults. Application of a simple formula encompassing 400-m time in seconds, number of steps for the first 20 m (<24 or ≥ 24) of the 2-minute walk, and SBP immediately after the 400-m walk provides an estimate of peak VO_2 superior to those derived from other indirect assessments. Time to walk 400 m can be used with the formula to estimate peak VO_2 or alone to identify persons with poor walking endurance suggestive of prevalent or impending mobility limitations. Incorporating low-cost, safe assessments of fitness in clinical and research settings can aid identification of critical risk factors for physical decline as well as individuals most in need of preventative intervention. Future work should focus on the prognostic value of the LDCW for functional and cardiorespiratory outcomes, including mortality and determination of clinically meaningful cutpoints.

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