Research Report

Maximal Voluntary and Functional Performance Levels Needed for Independence in Adults Aged 65 to 97 Years

Background and Purpose. Age-related loss of muscle mass and cardiovascular endurance can lead to impairments in muscle force production and cardiac function that, in turn, limit performance in activities essential to everyday living. The purposes of this study were: (1) to identify the "breakpoint" or threshold of maximal voluntary performance and performance in ordinary daily function and (2) to evaluate the predictive validity of the threshold to identify the ability to live independently without self-reported functional limitation. Subjects and Methods. Men and women (N=192; mean age=76 years, SD=7, range=65–97) were recruited from single-family community dwellings or retirement communities with multiple levels of care. Physical function was measured with the Continuous-Scale Physical Functional Performance Test (CS-PFP). Maximal voluntary performance measures included peak oxygen consumption ($\dot{V}O_{2peak}$) and isokinetic knee extensor torque (KET). Segmented linear regression models of the CS-PFP on the physical performance measures were used to determine the threshold values and their confidence intervals. A logistic regression model was used to evaluate the ability of the CS-PFP scores to identify those living independently and to further illustrate the concepts of threshold and physical reserve. Results. Threshold values identified for $\dot{V}O_{2peak}$ (20 $mL \cdot kg^{-1} \cdot min^{-1}$) and KET (2.5 $N \cdot m/[kg \cdot m^{-1}]$) were associated with an average of CS-PFP score of 57 units. The threshold accurately predicted individuals reporting functional limitations. Discussion and Conclusion. The thresholds provide a mechanism for easily estimating an individual's physical reserve, predicting dependency in living status, and providing unbiased guidance for intervention in late-life independence. [Cress ME, Meyer M. Maximal voluntary and functional performance levels needed for independence in adults aged 65 to 97 years. *Phys Ther.* 2003;83:37–48.]

Key Words: *Muscle torque, Oxygen consumption, Physical function, Physical reserve, Threshold.*

M Elaine Cress, Mary Meyer

Age-related loss of muscle mass and cardiovascular endurance can lead to impairments in muscle force production and cardiac function that, in turn, limit function, such as activities essential to everyday living.[1–3] These relationships are often described in the context of the disablement model, where "disability" refers to difficulties in carrying out socially defined tasks.[4] Underlying impairments (eg, lack of muscle force or endurance) often contribute to functional limitations (eg, being unable to walk to stores).[5] These disabilities can even lead to institutionalization.[6] When predicting disability, the importance of accounting for demands of the tasks a person needs to accomplish is often overlooked.[7] Depending on the difficulties encountered, disability may occur due to environmental demands.[8] While aging in the same environment, an individual may eventually have difficulty negotiating home and community in order to fulfill daily needs unless modifications in those environments take place. For example, limitations in walking, driving, or taking a bus may impede a person's ability to obtain groceries and, therefore, to live without assistance in a single-family dwelling.[8]

In this article, we examine 3 levels of the disablement model: impairment, functional limitation, and disability. For impairment in our study, we measured *maximal voluntary performance* for aerobic capacity and maximal voluntary muscle torque. Aerobic capacity is reported as peak oxygen consumption,[9] and muscle torque is reported as maximal voluntary muscle torque for the quadriceps femoris muscles.[10] Protocols for maximal voluntary performance measures were developed in an effort to isolate the variable of interest—aerobic capacity or maximal voluntary force—and to minimize the influence of other factors. When these protocols are adhered to strictly, these continuous-scale measures are reproducible and valid.[9,10] In our view, the advantages of these measures are that they are well-established markers of physical conditioning that are frequently reported in the literature. *Functional limitations* have been defined as the gap between a person's capabilities and the demands of the environment.[11] The "functional limitation" component of the disablement model was assessed using 2 methods: measurement of performance-based physical function and measurement of self-reported physical function. We use the term "physical function" to refer to the continuous-scale performance-based measure of everyday tasks important for living independently. The term "functional limitation" is used exclusively when referring to self-reported limitation in the ability to do tasks necessary for basic activities-of-daily living. The "disability" component of the disablement model is reported as a dichotomous independent-dependent variable based on the level of function limitation reported. Living environment is also reported. Participants resided in detached single-family houses, were community dwellers, or resided in continuous care retirement facilities.

Maximal voluntary performance declines begin in the fourth decade,[12] whereas marked increases in the prevalence of disability associated with aging do not occur until after the age of 75 years.[13] The delay in the loss of function relative to that of the loss of maximal voluntary performance, in our opinion, may be attributed to physical reserve (ie, maximal voluntary performance in excess of that needed to perform daily functions). Physical reserve can provide a "margin of safety" against functional decline.[14] Below the threshold, function decreases are more closely associated with loss of maximal voluntary performance.[1,15] Age-related loss of maximal voluntary performance, in our view, erodes physical reserves. Williamson and Fried[16] contended that, in the early stages of physical decline, people use modification strategies to cope with the demands of independent living (eg, cooking fewer meals, using only a portion of the home). Modification strategies most likely can forestall disability for a limited period of time in most people[16]; however, reserves depleted below the level required by daily demands can eventually lead to disability, depending on the environment.[15]

In this article, we provide an analysis of the relationship between commonly reported measures of maximal vol-

ME Cress, PhD, FACSM, is Associate Professor, Department of Exercise Science and The Gerontology Center, University of Georgia, 300 River Rd, Athens, GA 30602-6554 (USA) (mecress@coe.uga.edu). Address all correspondence to Dr Cress.

M Meyer, PhD, is Assistant Professor, Department of Statistics, University of Georgia.

Dr Cress provided concept/idea/research design, writing, data collection, project management, fund procurement, subjects, facilities/equipment, institutional liaisons, and consultation (including review of manuscript before submission). Dr Meyer provided data analysis.

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untary performance and what we view as clinically relevant measures of physical function. The first purpose of our study was to explore the relationships between the measures of maximal voluntary performance and physical function in order to identify the breakpoint or threshold between physical function and 2 maximal voluntary performance measures. The second purpose of our study was to evaluate the utility of using the threshold to assess the "ability to live independently," based on self-reported function in older adults with a broad range of abilities.

Method

Subjects

Older men and women were recruited from the greater Seattle area through advertisements and presentations at churches, senior centers and retirement communities. Participants were interviewed over the telephone using a standardized dialog and questionnaire to determine eligibility. Men and women 65 years of age or older were included. We minimized exclusion criteria in order to be as inclusive as possible for generalizability of the results. The following exclusion criteria were determined from the telephone interview selected to minimize injury to or complications for volunteers. People with unstable cardiovascular or metabolic disease, recent unhealed fractures, disorders with a highly variable course (eg, multiple sclerosis), pacemakers, life expectancy of less than 1 year, excessive alcohol intake (more than 2 drinks per day), or inability to speak English were excluded. People who were unable to keep the testing appointments at several different testing sites also were excluded from participation. Eligible volunteers received a history and physical examination from the study health care provider to verify eligibility and written informed consent was obtained from all participants.

Participants were categorized as belonging to 1 of 3 groups using information from both where the participant was living (single family dwelling or congregate care facility) and the extent of functional limitation that was reported. Two groups lived independently: (1) participants who lived in detached single-family dwellings are referred to as the "community dweller" (CD) group, and (2) residents of a congregate care facility who reported little or no functional limitation are referred to as the "congregate care facility/independent" (CCF/I) group. The third group was the categorized as dependent. These participants lived in a congregate care facility and reported significant functional limitation. We refer to this group as the "congregate care facility/dependent" (CCF/D) group. Functional limitation was based on the responses to the Medical Outcomes Study 36-Item Short-Form Health Survey [SF-36] Physical Function scale [SF-36PF].[17] Community dwellers have an inherently more demanding living environment than residents of a congregate care facility, where multiple supportive services,[8] such as meal service and light housework, are provided and professional care assistance can be readily obtained. Residents of a congregate care facility lack the compulsory physical challenge of community dwelling. Therefore, a person who has not tried walking more than 1.6 km (1 mile), for example, may fail to recognize the limitation and report "not limited at all." Once physical function has declined to a level where limitation is encountered on a daily basis, such as climbing a flight of stairs, then limitations in these tasks and in more demanding tasks can be recognized and reported.

The SF-36PF, a domain of the well-established SF-36 questionnaire,[17] was used to reflect functional limitation in performing daily tasks. The SF-36 is a valid and reliable measure of health status,[17] and it has been used with people with a diversity of diseases.[18,19] In the absence of data at the time we designed this study we used a score of <65 units as the criterion for the SF-36PF for the group we called "dependent." This criterion (<65 on the SF-36PF) was selected because it reflected a measure of self-reported limitation that included limitation on more than 2 items and we hoped to avoid categorizing participants as physically dependent when they were not physically dependent. To our knowledge, this is the first study to report maximal voluntary and physical functional performance relative to the SF-36PF scale. To attain a score of <65, an individual would have to indicate that he or she was "limited a little" on at least 7 items, or "limited a lot" on 3 items and "limited a little" on 1 item. Participants rated their function on the following tasks: vigorous and moderate activity; climbing one and several flights of stairs; walking more than 1.6 km, several blocks, and one block; lifting or carrying groceries; bending or stooping; and bathing or dressing. All community dwellers reported little or no functional limitation (SF-36PF score of ≥ 65 units). All participants who scored ≥ 65 units and lived in a congregate care facility were categorized as "independent" (CCF/I group). Both community dwellers and residents of a congregate care facility who scored ≥ 65 units, therefore, were categorized as living independently. Congregate care facility residents who reported functional limitation by scoring <65 units on the SF-36PF were categorized as "dependent" (CCF/D group).

Maximal Voluntary Performance Measures

Aerobic capacity. Maximal oxygen consumption ($\dot{V}O_2$), a well-established measure of cardiovascular fitness, has been reliably measured in older adults.[20] We used a cycle ergometer to elicit peak oxygen consumption ($\dot{V}O_{2peak}$) in an effort to allow participation of individuals who

were unable to ambulate the 1 mph necessary to walk on a treadmill. Participants were allowed to become familiar with the cycle ergometer prior to the aerobic capacity test. Using a ramp-testing protocol, power output was increased at a fixed rate (8–16 $W \cdot min^{-1}$) on a MedGraphics CPX electronically braked cycle ergometer.* Expired air was analyzed using MedGraphics zirconia fuel cell oxygen and infrared carbon dioxide analyzers.* Gas flow was measured using a pneumotach and a waveform analyzer. Data were averaged over an 8-breath period, and the final report was for every 30 seconds. A physician continuously monitored the 12-lead Quinton Q650 electrocardiogram† (ECG) throughout the test, and heart rates were recorded every 30 seconds. The following criteria are often used as evidence of maximal effort: (1) maximum achieved heart rate within 10 bpm of age-predicted maximum heart rate,[21] (2) respiratory exchange ratio of >1.0,[22,23] or (3) rating of perceived exertion of at least 18 on the Borg 6–20 Rating of Perceived Exertion Scale.[24,25] Criteria for test termination included participant fatigue, signs and symptoms of exercise intolerance, ECG changes, and abnormal blood pressure or respiratory response. Aerobic capacity data are reported as $\dot{V}O_{2peak}$ in order to include as many individuals as possible, rather than excluding data based on the criteria for maximal effort.

Data collected included peak heart rate, $\dot{V}O_{2peak}$, respiratory exchange ratio, and rating of perceived exertion. Tests were run in the Harborview Medical Center's Pulmonary Functional Laboratory, Seattle, Wash.

Maximal voluntary muscle performance. Isokinetic knee extensor torque (KET) was measured on a LIDO isokinetic dynamometer‡ at 60°/s using gravity correction and was recorded as maximal voluntary torque (in newton-meters). Cress et al[26] found this instrument to provide reproducible measurements (r=.93, n=25) when measuring maximal voluntary knee extensor torque in older adults. The force generated by the quadriceps femoris muscle is important to functional ability in stair climbing and rising from a chair.[14,27,28] The quadriceps femoris muscle was selected for clinical relevance, and 60°/s was chosen for consistency with other studies.[29,30]

Prior to testing, participants warmed up on a cycle ergometer for 5 minutes, after which familiarization on the isokinetic dynamometer included 5 warm-up knee extensions. The maximal voluntary torque was the highest recorded torque of 4 successive maximal efforts. Data were collected at Northwest Rehabilitation Hospital Outpatient Clinic, Seattle, Wash.

Functional Measures

Continuous-Scale Physical Function Performance Test (CS-PFP). The CS-PFP was developed from data on older adults with a broad range of physical abilities.[31] In previously published research, this test has been shown to have convergent, construct, and face validity for 16 everyday household tasks.[31] It has high reproducibility (r=.97).[31] It is sensitive to change induced by exercise, with an effect size of 0.8.[32] The CS-PFP is specific for physical function and is not related to emotional or mental health or to depression.[31] A detailed description of the procedure for administration of the CS-PFP is published elsewhere.[31] The CS-PFP is based on ordinary activities of daily life, performed at maximal effort within the bounds of safety and comfort. It was administered under standard conditions at Northwest Rehabilitation Hospital, Easy Street Environments, Seattle, Wash, using instructions from a script.

Sixteen tasks are administered, and a combination of time, distance, and weight is used to quantify performance. Tasks quantified using both weight and time include: (1) carrying of weight, (2) pouring water from a jug into a cup, (3) carrying weight up and down a bus platform, and (4) carrying groceries. Tasks quantified by time alone include: (1) transferring laundry from a washer to a dryer, (2) putting on and removing a jacket, (3) floor sweeping, (4) vacuuming, (5) making a bed, (6) climbing stairs, (7) getting down and up from the floor, (8) pulling open a fire door, (9) putting a Velcro closed strap§ over a shoe, and (10) picking up 4 scarves from the floor. Tasks that are quantified by distance alone include: (1) a 6-minute walk and (2) highest reach. Each task is scored from 0 to 100 based on an empirically derived range from data gathered on older adults with a broad range of capabilities.[32] Time was used to calculate speed ($1/t$), so that higher numbers reflected higher function for each unit of measure (weight, distance, and speed). Each task is scaled 1 to 100 according to the following formula:

$$\text{Observed score} = (\text{observed scored} - \text{lower limit}) / (\text{upper limit} - \text{lower limit}) \times 100.$$

The total physical functional performance score (CS-PFP total) is the average corrected score of all tasks. The specifics of the test and scoring are available at: http://www.coe.uga.edu/cs-pfp/.

* Medical Graphics Corp, 350 Oak Drive Pkwy, St Paul, MN 55127-8599.
† Quinton, 3303 Monte Villa Pkwy, Bothell, WA 98021.
‡ Loredan Biomedical Corp, PO Box 1154, Davis, CA 95617.
§ Velcro USA Inc, 406 Brown Ave, Manchester, NH 03103.

Self-reported physical function. The SF-36PF[18] was used to assess self-reported functional limitation and categorize the participants as "independent" or "dependent." The details of this measure are presented in the "Subjects" section.

Data Analysis

An analysis of variance (ANOVA) was used to examine differences among the groups of subjects on descriptor variables (ie, age, height, and weight), functional variables (SF-36PF, CS-PFP) and maximal voluntary performance variables (ie, $\dot{V}o_{2peak}$ and isokinetic knee extensor torque), physiological criteria for peak oxygen consumption (ie, peak heart rate respiratory exchange ratio and rating of perceived exertion). The Tukey honestly significant difference pair-wise multiple-comparisons test was used to look for differences between each pair of means at an alpha level of .05. The ANOVA was performed using the SPSS Version 10 software program.[‖]

Modeling. The model chosen to describe the nonlinear relationship between the maximal voluntary performance measures and physical function was a "segmented" line.[33] A scatterplot of CS-PFP scores against $\dot{V}o_{2peak}$ measurements is shown in Figure 1A, and a scatterplot of CS-PFP scores against KET measurements is shown in Figure 1B. The least-squares fit using the segmented line is shown in each figure. The scatterplots show that a single straight line is not an adequate model. The trend of the points was "steeper" for smaller maximal voluntary performance and function values and "flatter" for higher maximal voluntary performance values. Often, a quadratic model is chosen to represent a nonlinear relationship, but this model would be inappropriate here. The least-squares fit to the scatterplot in Figure 1A, using a quadratic model, is a parabola with maximum CS-PFP score at around 32 units of $\dot{V}o_{2peak}$. This least-squares fit would predict smaller values of physical functioning when conditioning increases, which is not a valid representation of the true relationship.

The segmented-line model is the simplest mathematical equation that fits the data and has a valid interpretation. Furthermore, this model produces a natural threshold (defined at the "breakpoint"). The segmented linear function is written:

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 (x_i - c) t_i + \varepsilon_i$$

for $i = 1, \ldots, n$. The x_i are observations of the independent variable (KET or $\dot{V}o_{2peak}$); the t_i are the threshold indicators, where t_i is 1 if the participant's scores are above the threshold and 0 if the participant's scores are below the threshold; and y_i are observations of the dependent variable (CS-PFP score). This segmented line described by the model is continuous, with 2 slopes, as shown in Figures 1A and 1B. The parameter β_1 represents the slope below the threshold, and the slope above the threshold is $\beta_1 + \beta_2$, so that the difference in slope is β_2. The parameter c represents the threshold value, and β_0 is the intercept. The error terms represented by ε_i are assumed to be identically distributed and uncorrelated. The least-squares estimates for β_0, β_1, β_2, and c, for both models, were obtained with standard nonlinear regression techniques, and the asymptotic covariance matrix for the parameter estimates was used to establish estimates of the 95% confidence intervals (CIs).[34] The *threshold range* may be defined as the limits of the 95% CI for either physical performance or aerobic capacity.

Separate models were used to relate physical function to the 2 measures of maximal voluntary performance. We chose separate models for both ease of use and ease of interpretation. First, physical reserve may be estimated even when only one maximal voluntary performance measure is available. Because maximal voluntary muscle force and aerobic capacity are highly correlated, it could be argued that only one measure of maximal voluntary performance is necessary. However, some individuals might have more aerobic capacity in reserve than maximal voluntary muscle force to draw upon to be used by their muscles. Knowing this may be important for intervention purposes. Second, if we choose to include both maximal voluntary performance variables in the same model, it is not clear how to define threshold. Further, possible confounding effects and interaction between the maximal voluntary performance variables were likely because of the high correlation, making the results difficult to interpret.

Predictive validity. A logistic regression model was used to illustrate the relationship between physical function and independence as defined by group. A dichotomous independent-dependent variable based on where a person lives and the level of self-reported function limitation was created. The independent group comprised community-dwelling subjects and subjects in the CCF/I group. The dependent group comprised subjects in the CCF/D group. A logistic regression model was used to predict those in the CCF/D group from the CS-PFP score.

Results

Subject Description

The 192 volunteers ranged in age from 69 to 97 years. All 98 community dwellers rated their physical function as ≤70 on the SF-36PF. Of the 94 participants who lived in

[‖] SPSS Inc, 233 S Wacker Dr, Chicago, IL 60606.

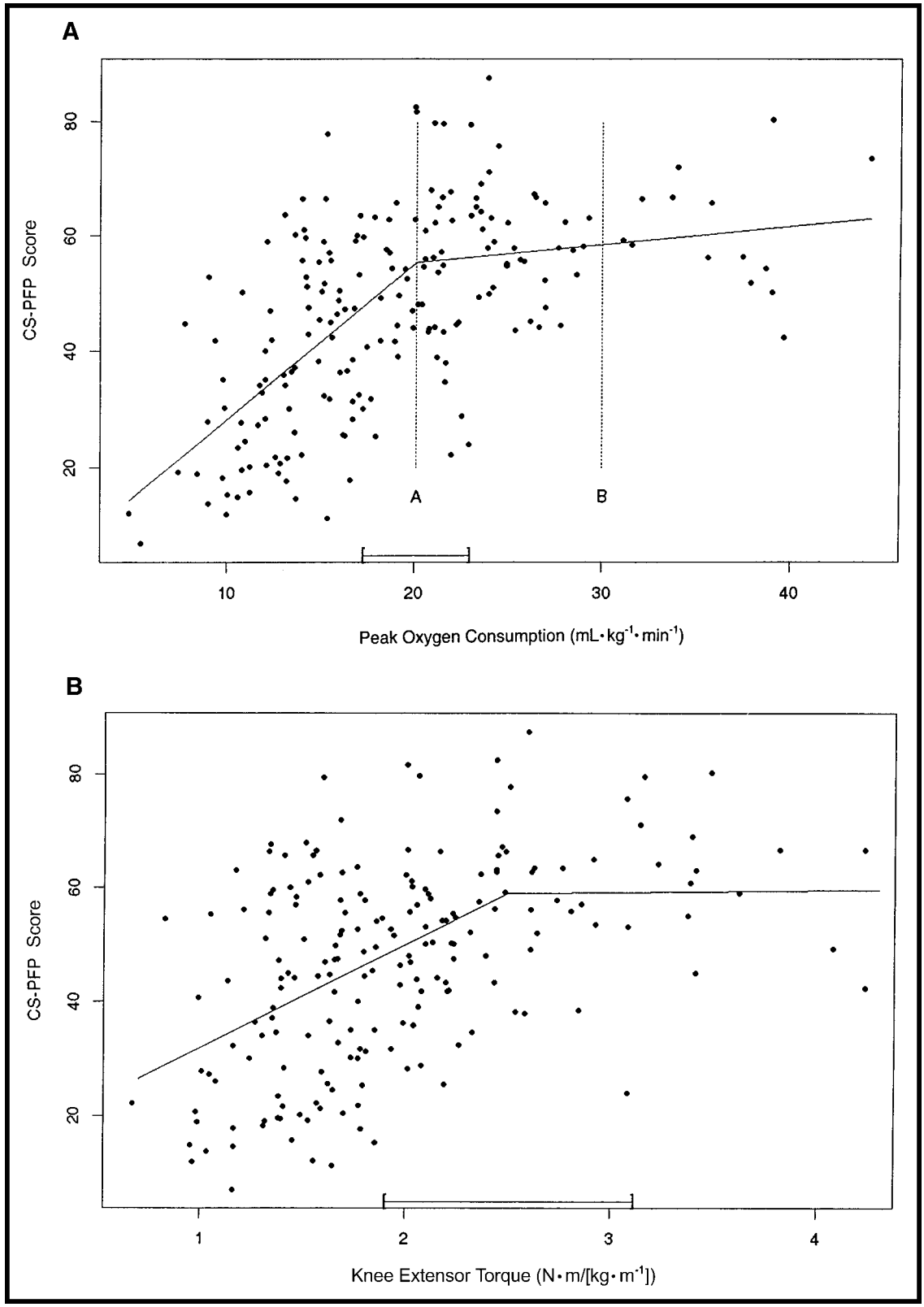

Figure 1A. Piece-wise linear regression of peak oxygen consumption ($\dot{V}O_{2peak}$) measurements (in milliliters per kilogram per minute) and Continuous-Scale Physical Functional Performance Test (CS-PFP) scores. Points A and B represent different physical reserves. If point B loses 8 $mL \cdot kg^{-1} \cdot min^{-1}$ of aerobic capacity, the loss in physical function is a CS-PFP score of approximately 3 units (8×0.32). If point A loses 8 $mL \cdot kg^{-1} \cdot min^{-1}$ of aerobic capacity, the expected drop in function would be a CS-PFP score of approximately 21 units (8×2.67); |—| designates the 95% confidence interval for the $\dot{V}O_{2peak}$ measurements. **Figure 1B.** Piece-wise linear regression of knee extensor torque measurements (maximal voluntary torque at 60°/s) adjusted for body height and weight (newton-meter/[(body weight in kilograms)/(body height in meters)]). |—|designates the 95% confidence interval for maximal voluntary torque measurements.

a congregate care facility, 49 were categorized as independent (CCF/I group) based on their SF-36PF score of #65, with the remaining 45 subjects categorized as dependent (CCF/D group) based on an SF-36PF score of <65. Selected demographic characteristics, health status, and primary measures are listed in Table 1. The SF-36PF scores were similar for the independent groups, whereas the CCF/D group had more functional limitation.

Maximal Voluntary Performance

The CCF/D group had lower maximal voluntary performance levels than the independent groups (CCF/I group, community dwellers). The group means and standard deviations for $\dot{V}O_{2peak}$ and for isokinetic knee extensor torque are shown in Table 1. Eighty percent of the subjects (n=154) met 2 of the 3 criteria for maximal effort on the aerobic capacity test, indicating that the majority met the criteria for maximal effort. However, data from those subjects who did not meet the criteria for maximal effort were included in the physical threshold analysis in an effort to allow for greater generalizability of the data. The distribution across groups of those meeting these criteria is shown in Table 1.

Physical Thresholds

We first examined the relationship between maximal voluntary performance measures and physical function for the presence of a threshold. The parameter estimates in Table 2 indicate that the threshold for $\dot{V}O_{2peak}$ was 20.1 $mL \cdot kg^{-1} \cdot min^{-1}$ (95% CI=17.33, 22.92). Below the threshold, the best segmented linear fit was a slope of 2.67 (slope β_1), so that for each unit change in $\dot{V}O_2$, the average change in the CS-PFP score was 2.67 units. The slope above the threshold was much shallower, at 0.32, a number obtained by subtracting the difference in the slope β_2 (−2.35) from the slope β_1 (2.67). Above the threshold, we found that each unit change in $\dot{V}O_2$ represented a change of less than 1 unit in the CS-PFP score. The graph in Figure 1A illustrates that the functional benefit for each unit increase in $\dot{V}O_2$ below the threshold was more than 8 times higher than for each unit change in $\dot{V}O_2$ above the threshold.

The parameter estimates for the maximal voluntary muscle torque threshold ($N \cdot m/[kg \cdot m^{-1}]$) are also shown in Table 2. Figure 1B shows the fit of the model to the scatterplot of CS-PFP scores against KET measurements on the x-axis. The threshold was 2.5 $N \cdot m/(kg \cdot m^{-1})$ (95% CI=1.91, 3.11). The slope below the threshold was 17.5 (slope β_1), whereas above the threshold, the slope was 0.9 (95% CI=17.5, 16.6). Below the threshold, each increase in torque yielded a benefit to physical performance with a CS-PFP score of 17.5 units, that is, approximately 20 times more than we found above the threshold, with a CS-PFP score of 0.9 unit.

The CS-PFP score associated with the thresholds for KET measurements was 58.1 units, and the CS-PFP score for $\dot{V}O_{2peak}$ was 55.3 units (Tab. 2), for an average CS-PFP score of 57 units. The term "CS-PFP threshold" will refer to the average CS-PFP value at the physical performance thresholds; that is, the CS-PFP threshold is 57 units. The fact that both maximal voluntary performance thresholds, obtained from separate models, are associated with approximately the same CS-PFP score is evidence that these models are valid descriptors of the relationship between these 2 physical performance measures.

Predictive Validity

Using a logistic regression model, we evaluated the ability of the threshold value for the estimated physical function threshold to accurately predict independence (community dwellers or the CCF/I group) for 192 individuals. The CS-PFP score was used as the predictor variable in the logistic regression. This model was chosen as the most commonly recognized probability curve to illustrate this relationship. The participants were grouped as independent (1) and dependent (0), which is the response variable in the logistic regression. Participants in the community-dwelling and CCF/I groups were categorized as 1, and those in the CCF/D group were classified as 0. The chi-square test statistic of 109.21 for the statistical analysis corresponds to a probability value of <.0001. The predictive validity of the CS-PFP scores is illustrated in Figure 2, where the points represent the participants, with the independent individuals at the top and those categorized as dependent at the bottom. Of those with a CS-PFP score above the CS-PFP threshold of 57 units, all were living independently, 79% were community dwellers, and the remaining participants were residents of a congregate care facility. Of those with a CS-PFP score below the CS-PFP threshold, 57% were living independently, 30% were living as community dwellers, and the remaining 27% were living as residents of a congregate care facility who did not have self-reported functional limitation. The curve in the plot represents the probability of independence at a given level of the predictor as estimated with the logistic regression.

Discussion and Conclusions

We found distinct thresholds for both maximal voluntary torque and aerobic capacity with respect to performance in tasks common in everyday life. The $\dot{V}O_{2peak}$ threshold of 20.1 $mL \cdot kg^{-1} \cdot min^{-1}$ and maximal voluntary muscle torque threshold of 2.5 $N \cdot m/(kg \cdot m^{-1})$ were both associated with similar CS-PFP scores of 55 and 58, respectively. Although younger adults and older adults without known pathology can be expected to have adequate physical reserve as a buffer against unexpected demands or temporary decline in maximal voluntary performance (eg, acute illness),[15] those who experience declines in

Table 1.
Participant Characteristics by Living Status[a]

Variable	CCF/D Group	CCF/I Group	CD Group
No. of subjects	45	49	98
Age (y)			
$\bar{X}$	84[c,d]	79[c]	74
SD	7	6	3
Range	70–97	70–93	69–84
Height (cm)			
$\bar{X}$	157[c,d]	163[c]	166
SD	9	9	9
Range	140–188	139–179	151–188
Weight (kg)			
$\bar{X}$	67.8	65.5	65.3
SD	10	10	11
Range	49–87	46–86	48–100
% female	91	78	70
Education beyond high school[b]	90	92	92
% Caucasian	100	94	95
% with an annual income of ≥$20,000 (no. of subjects who refused to answer)	74 (24)	70 (16)	69 (5)
SF-36PF score			
$\bar{X}$	47.3[c,d]	86.8	90.2
SD	13	9	8
Range	15–60	65–100	70–100
CS-PFP score			
$\bar{X}$	25.7[c,d]	46.3[c]	56.9
SD	10	16	11
Range	7.0–48.8	17.7–82.3	32.9–87.4
Isokinetic knee extensor torque (maximal voluntary torque at 60°/s) (N·m)			
$\bar{X}$	59.47[c,d]	78.78[e]	94.93
SD	17.4	26.4	36.2
Range	34–111	41–155	53–206
Peak oxygen consumption ($mL \cdot kg^{-1} \cdot min^{-1}$)			
$\bar{X}$	12.78[c,d]	16.84[c]	21.11
SD	3.8	4.0	6.8
Range	4.7–22.54	9.88–26.97	9.03–44.25
Peak heart rate (bpm)			
$\bar{X}$	126[c]	135	142
SD	19	19	20
Range	88–158	83–176	98–187
Respiratory exchange ratio			
$\bar{X}$	1.07[e,f]	1.18[e]	1.15
SD	0.1	0.1	0.1
Range	0.78–1.38	0.86–1.41	0.89–1.39
Rating of perceived exertion			
$\bar{X}$	15.3	16.2	15.63
SD	1	2	2
Range	11–20	11–19	11–19
% meeting 2 or more criteria for maximal oxygen consumption	62	77	90

[a] CCF/D=congregate care facility residents who reported functional limitation by scoring <65 units on the Medical Outcomes Study 36-Item Short-Form Health Survey Physical Function scale (SF-36PF) and were categorized as "dependent." CCF/I=congregate care facility residents who reported functional limitation by scoring ≥65 units on the SF-36PF and were categorized as "independent." All community dwellers (CD group) reported little or no functional limitation (SF-36PF score of ≥65 units). CS-PFP=Continuous-Scale Physical Functional Performance Test.
[b] Attended college, technical school, or trade school.
[c] Significantly different from CD group, $P<.001$, Tukey honestly significant difference test; within-group $df=189$, between-group $df=2$.
[d] Significantly different from CCF/I group, $P<.001$.
[e] Significantly different from CD group, $P<.05$.
[f] Significantly different from CCF/I group, $P<.05$.

Table 2.
Least-Squares Parameter Estimates for Segmented Linear Regression (N=192)[a]

Parameter	$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) Estimate (95% CI)	Knee Extensor Torque ($N \cdot m/[kg \cdot m^{-1}]$) Estimate (95% CI)
R^2	.40	.24
Intercept β_0	1.55 (−9.62, 12.72)	14.3 (4.1, 24.5)
Slope β_1	2.67 (1.92, 3.42)	17.5 (11.8, 23.2)
Difference in slope β_2	−2.35 (−3.28, −1.43)	−16.6 (−29.2, −4.1)
Threshold c	20.13 (17.33, 22.92)	2.5 (1.91, 3.11)
CS-PFP value associated with physiological thresholds	55.30 (47.8, 56.2)	58.05 (47.7, 58.6)

[a] CS-PFP=Continuous-Scale Physical Functional Performance Test, $\dot{V}O_{2peak}$=peak oxygen consumption, R^2 and the 4-parameter estimates with 95% confidence intervals (CIs) for the piece-wise linear fit for the 2 maximal voluntary performance measures ($\dot{V}O_{2peak}$ and knee extensor torque) and the corresponding CS-PFP threshold. For each analysis, the maximal voluntary performance measures ($\dot{V}O_{2peak}$ and knee extensor torque) are independent variables, and CS-PFP is the dependent variable. The model has 4 parameters: the intercept β_0, the slope β_1, the difference in slope β_2, the threshold c.

fitness can have a proportional decline in function.[35] Physical inactivity is associated with poor muscle force production, which, in turn, can limit mobility, which then often leads to further limitations in physical activity.[5] This downward spiral is thought to erode physical reserves, potentially jeopardizing physical independence[36] in older adults. Greater force production is associated with better functional performance.[31,37,38] Muscularly generated force over and above that needed for routine daily functioning provides a physical reserve or possibly a margin of safety.[14,29]

There is a growing need to have measures that go beyond functional limitation and capture functional ability. Although the concept of a margin of safety has been discussed in the literature,[14,35] it has not been quantified. We used the following formula to calculate a physical reserve:

Physical reserve=maximal voluntary performance (aerobic capacity or maximal voluntary muscle torque)−threshold (aerobic capacity or maximal voluntary muscle torque)

In Figure 1A, the dotted lines at points A and B represent 2 people with similar CS-PFP scores but very different aerobic capacities. The person at point A, near the threshold, had less aerobic capacity and therefore a smaller safety margin than the person at point B, with a $\dot{V}O_{2peak}$ that was considerably above the threshold. For the same loss in aerobic capacity a person at point A would sustain an 8-fold greater loss in physical function than a person at point B. Likewise, for the same loss in maximal voluntary muscle torque, the person at the threshold would have 20 times the loss in physical function than someone with a maximal voluntary muscle torque above the threshold. Longitudinal studies are needed to understand the impact of loss in either muscle force production or aerobic capacities on physical function. For example, a loss of $\dot{V}O_{2peak}$ without a concomitant loss of muscle force may attenuate the loss of function. This relationship has been illustrated by Buchner and associates.[37] The nature of the decline in $\dot{V}O_{2peak}$ relative to maximal voluntary torque is not well defined; thus, an associated loss of physical function may not be accurately reflected by either of these measures alone.

The probability curve (Fig. 2) shows the person-environment fit using the CS-PFP threshold to predict the physical ability needed to live independently. The steep drop in the probability that an individual is able to live independently as CS-PFP score decreases below the threshold value of 57 units is an illustration of both the threshold concept and the physical reserve concept. Above the CS-PFP threshold of 57 units, the probability curve was flatter and near 1. These results indicate that people with a physical reserve (CS-PFP score of >57 units) do not report limitations (Fig. 2, top right). Subjects with CS-PFP scores of >57 had the "margin of safety" conceptualized by the physical reserve. These individuals can lose physical function without losing their ability to live independently, but, at the threshold, further losses in function are associated with drastic declines in the probability of having the ability to live independently.

Our data indicate that individuals with less self-reported limitations have poor physical performance (Fig. 2, bottom left). One hundred percent of those in the CCF/D group performed below the CS-PFP threshold, with average CS-PFP scores of 26 units (SD=10). These individuals all rated themselves as limited in physical function (mean SF-36PF score=47, SD=13) and lived in a congregate care facility, an environment where they could obtain assistance if needed. The environment, self-reported function, and their ability to perform daily tasks were all in agreement.

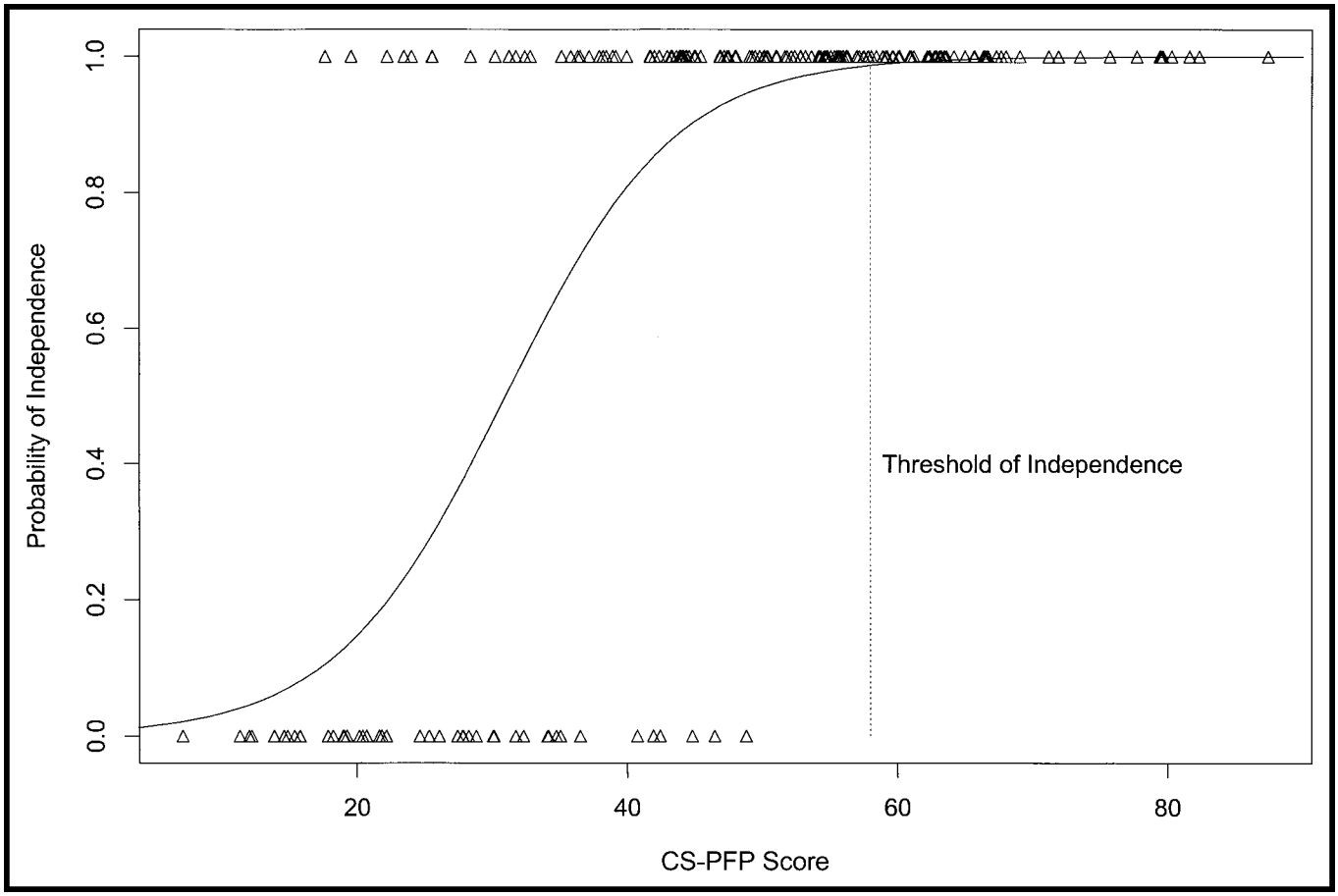

Figure 2.
Graph reflects the probability of independence estimated by logistic regressions for Continuous-Scale Physical Functional Performance Test (CS-PFP) scores as a predictor variable. The points (triangles) represent subjects; the x-coordinate represents CS-PFP scores. Those points at the top represent subjects with living status CD (community dwelling) or CCF/I (congregate care facility residents who reported functional limitation by scoring ≥65 units on the Medical Outcomes Study 36-Item Short-Form Health Survey Physical Function scale [SF-36PF] and were categorized as "independent"); those at the bottom represent subjects with living status CCF/D (congregate care facility residents who reported functional limitation by scoring <65 units on the SF-36PF and were categorized as "dependent"). The curve represents the probability of "independent" living status (CD or CCF/I) as estimated by the logistic regression on CS-PFP scores (intercept estimate = −4.96, standard error=0.895, $\chi^2 = 109.21$).

None of the people who saw themselves as having limitations (SF-36PF score of <65 units) performed above the physical threshold (CS-PFP score of >57 units) (Fig. 2, top left). The CCF/I group had a higher level of physical performance and self-reported functional limitation, with an average CS-PFP score of 46.3 units (SD=16) and an average SF-36PF score of 87 units (SD=9), respectively. Some of the most compelling data from this study were gathered on those subjects who were living in the community without recognized functional limitations (SF-36PF score of ≥65 units), yet their physical performance was below the physical threshold as defined by the CS-PFP score of 57 units. Of these participants, approximately half lived in a single-family home. These individuals, living with high environmental demand and low physical function, may implement modification strategies such as using only a portion of their home in order to accommodate lower physical capacities[16] or have the social support necessary to meet the demands of daily life.[8] Future studies are needed to identify risks, delineate mechanisms, and identify strategies to assist those wanting to live the later years in the family home in the face of dwindling physical reserves.

In this study, we used a self-reported functional limitation score of 65 units on the SF-36PF to categorize independent and dependent categories. Ten questions were used to assess the range of activity, from vigorous activity to bathing, dressing, and feeding. The questions on performance of vigorous activity and of bending and stooping were the most frequently reported functional limitations. Other researchers[19,39,40] have used a self-reported functional limitation score of 85 units on the SF-36PF as an indication of disability. Had we used a self-reported functional limitation score of 85 units rather than that of 65 units, 10 community dwellers would have been listed as dependent. With an average CS-PFP score of 59 units (range=49–62), all 10 of these individuals scored above the lower limit of the CS-PFP threshold CI (95% CI=47, 58; Tab. 2). However, those

subjects with self-reported functional limitation scores between 65 and 85 units on the SF-36PF and living in a supportive environment (congregate care facility) had an average CS-PFP score of 35 units (range=28–42), well below the CI for the CS-PFP threshold. These individuals did not have a physical reserve and may have been on the brink of experiencing physical disability. Using the score of 85 units on the SF-36PF as an indicator of disability may overestimate disability for those living in a high-demand environment (eg, community dwellers) but not for those in a supportive environment. These data provide evidence that a performance-based measure of physical function is better at discriminating functional ability for those close to experiencing physical disability than a self-reported functional limitation measure.

Our threshold data can be used in a variety of ways: (1) to gain insight into levels of supportive services needed by older adults; (2) to help a person attain a particular level of force production, augmenting the physical reserve, prior to the interruption of an exercise program, such as for elective surgery or vacation; and (3) to monitor the progression in an exercise program and help determine when a person should move into a maintenance phase of training. Prospective studies are needed to determine whether older adults with low physical function who continue to live in a high-demand environment are at greater risk for falls or other serious medical events. Finally, research is needed to determine whether these thresholds can be used to identify levels of impairment that lead to functional limitation and subsequent disability.

We did not exclude people who did not meet the criteria for maximal $\dot{V}o_2$ or perform twitch interpolation procedures to determine maximal knee extensor torque. The maximal voluntary performance results reported here may not reflect the true maximal physical ability of our entire group; thus, in some instances, the physical reserve may be underestimated for some individuals. However, these data may be more reflective of the physical ability accessible to this population. Therefore, we did not exclude participants because of failure to meet criteria for maximal effort in an effort to be as inclusive as possible. In our judgment, the results of this study should not be generalized beyond the population tested (ie, primarily well-educated Caucasians from middle and higher socioeconomic groups). There is considerable concern about the physical function and health status of minorities, who may exhibit different physical thresholds than those we found in this study.

In conclusion, these aerobic capacity and maximal voluntary muscle torque thresholds identify a range below which physical function is most affected by low fitness. Our findings indicate that individuals with self-reported functional limitations who live in a congregate care facility have $\dot{V}o_{2peak}$ and knee extensor torque below the thresholds of 20 $mL \cdot kg^{-1} \cdot min^{-1}$ and 2.5 $N \cdot m/(kg \cdot m^{-1})$, respectively. People with self-reported functional limitations are more likely need physical support such as living in a congregate care facility. The thresholds provide a mechanism for easily estimating an individual's physical reserve, predicting dependency in living status, and providing unbiased guidance for interventions aimed at late-life physical independence.

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