GET A GRIP AND DON'T WASTE YOUR BREATH: GRIP STRENGTH AND PEAK EXPIRATORY FLOW ARE STRONG PREDICTORS OF MORTALITY IN OLDER POPULATIONS

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ABSTRACT

Although previous studies have indicated that performance assessments strongly predict future survival, few have evaluated the incremental value beyond that of self-reported activity and mobility limitations. We assess and compare the added value of four tests: walking speed, chair stands, grip strength, and peak expiratory flow (PEF). Using population-based samples of older adults in Costa Rica and Taiwan, we estimate proportional hazard models of mortality for an approximate five-year period. Self-reported measures of physical limitations contribute substantial gains in mortality prediction, while performance-based assessments yield small incremental gains. PEF provides the greatest added value, followed by grip strength. For predicting mortality, our results suggest there is little to gain from including more than one or two performance assessments. PEF and grip strength are simpler to administer, impose less burden on the respondent, and are better predictors of mortality than walking speed or chair stands.

INTRODUCTION

Measures of physical performance and functional abilities have provided researchers and health professionals with valuable indicators of the current and future health status of community-dwelling populations of older adults. Population-based surveys frequently include such measures, either from self-reports or as interviewed-administered performance tests. Although these two types of measures—often labeled "subjective" and "objective" respectively—are statistically correlated, they are thought to capture distinct constructs (Reuben et al., 2004), and each has been shown to predict subsequent deterioration in health in diverse settings (Bernard et al., 1997; Cooper, Kuh, Hardy, Mortality Review Group, & FALCon and HALCyon Study Teams, 2010; Ferrucci et al., 1991; Guralnik, Ferrucci, Simonsick, Salive, & Wallace, 1995; Guralnik et al., 2000; Reuben, Siu, & Kimpau, 1992; Tinetti, Inouye, Gill, & Doucette, 1995).

Each method has advantages and drawbacks. The most frequently used self-reported measures identify: (1) limitations to perform basic activities of daily living (ADL) such as bathing or eating, and (2) mobility limitations such as walking or raising arms. These indicators are easy to collect, inexpensive, and focus on behaviors that are clinically relevant and signal the need for caregiving (Reuben et al., 2004). Although the subjective component of self-reports may capture information of prognostic value, self-reports are likely to be biased by myriad factors (e.g., environmental conditions, cultural preferences, or attitudes) that impede comparisons across populations or subgroups (Melzer, Lan, Tom, Deeg, & Guralnik, 2004) and may fail to identify differences among high-functioning individuals (Reuben et al., 2004).

Performance assessments, such as grip strength, peak expiratory flow (PEF), chair stands, and walking speed, are largely determined by physiological functions – muscle strength, speed, and cardiorespiratory function – that decline with age and may underlie frailty (Cooper et al., 2010). These measurements are considered to have greater face validity and perhaps reliability than self-reports, and are likely to be more sensitive to changes over time, more comparable across different contexts, and better suited to capturing variation across a continuum of physical function (Guralnik, Branch, Cummings, & Curb, 1989; Guralnik et al., 1994; Myers, Holliday, Harvey, & Hutchinson, 1993); some suggest that they provide "preclinical" detection of functional decline (Reuben et al., 2004). But they come at a cost, not only a monetary cost, but also one of respondent and interviewer burden. The tests are time-consuming, require substantial effort for some older or weak respondents, need special equipment and space for administering, and may compromise response rates for the overall survey. Thus, the decision about whether to include them in home-based interviews is likely to depend on their added value beyond information captured by self-reports.

This paper assesses the prognostic value of performance assessments for survival when self-reported measures are also available. Our primary objective is to ascertain the incremental improvement in mortality prediction derived from performance tests beyond that provided by self-reports. Our secondary objectives are to determine: whether some performance assessments are stronger predictors than others; whether their predictive power persists with controls for self-reported disease status; and whether their prognostic value varies by subgroup. To assess the robustness of our findings, we use data from two population-based surveys of older adults that collected similar information in Taiwan and in Costa Rica.

BACKGROUND

There has been little research addressing the central questions in this analysis. Few studies predicting all-cause mortality in a general population of older adults include both self-reported and performance-based assessments of physical function. Almost all existing studies are based in high income countries – primarily the US (Al Snih, Markides, Ray, Ostir, & Goodwin, 2002; Cook et al., 1991; Guralnik et al., 1994; Hardy, Perera, Roumani, Chandler, & Studenski, 2007; Markides et al., 2001; Melzer, Lan, & Guralnik, 2003; Reuben et al., 2004), but also Italy (Cesari et al., 2008) and Australia (Simons, Simons, Friedlander, & McCallum, 2011). Two exceptions are a study in China (Feng, Hoenig, Gu, Yi, & Purser, 2010) and another in Costa Rica (Rosero-Bixby & Dow, 2012).

Beyond this geographic restriction, existing studies have several drawbacks. First, although most studies include self-reported ADL limitations, few include self-reported mobility limitations, which afflict adults across a broader age range. Second, researchers often combine several different performance assessments into a summary measure, sometimes precluding evaluations of individual tests as predictors of mortality. For example, several studies use the Short Physical Performance Battery (SPPB), which comprises a timed walk, repeated chair stands and balance stands (Cesari et al., 2008; Guralnik et al., 1994; Hardy et al., 2007; Markides et al., 2001; Reuben et al., 2004), and one uses the MOBLI (Index of Mobility-Related Limitations), which replaces balance stands with PEF (Melzer et al., 2003). Finally, although researchers have speculated that the prognostic value of performance assessments may vary by age, sex, and the presence of self-reported functional limitations (Cesari et al., 2008; Cooper et al., 2010; Reuben et al., 2004; Rosero-Bixby & Dow, 2012), few have tested such interactions or stratified the analysis.

Despite variation in the measures collected and in the lengths of follow-up, most studies have found that performance tests predict mortality net of self-reported limitations. However, perhaps because of variations in study design, researchers disagree about which tests best predict mortality. For example, Cesari et al. (2008) found chair stands to be the strongest component of the SPPB in predicting mortality, whereas several earlier studies identified walking speed (Al Snih et al., 2002; Markides et al., 2001; Ostir, Kuo, Berges, Markides, & Ottenbacher, 2007). Rosero-Bixby & Dow (2012) found grip strength to be the strongest predictor of mortality in women, whereas PEF was the best predictor in men; walking speed was only marginally significant net of the other covariates. Most studies that have examined grip strength or PEF, in combination with self-reports, have included few, if any, additional performance assessments, making it difficult to evaluate these two measures vis-à-vis the others.

Our study extends the existing literature in several important ways. First, we examine whether previous findings, based mostly on the US, extend to two middle income countries: Taiwan and Costa Rica. Second, we consider a set of four performance tests to assess whether chair stands or timed walks – as some earlier work suggests – are the strongest predictors, or whether grip strength or PEF, which are often not part of the most frequently used batteries of tests, perform as well or better. Reducing the number or complexity of performance assessments is attractive not only to researchers, but also to clinicians who use them to screen for patients in need of caregiving or medical intervention. Third, we consider whether the prognostic value of these assessments varies by demographic and health characteristics. Specifically, within the middle-aged and older population, are the assessments more predictive for the elderly and are they stronger predictors for men than women? Such results would be consistent with tentative findings from a meta-analysis of several performance assessments

(Cooper et al., 2010). In line with results from the EPESE (Established Populations for Epidemiologic Studies of the Elderly) study in the US (Reuben et al., 2004), we also consider whether performance tests have greater prognostic value among those who report themselves to be highly functioning.

MATERIALS AND METHODS

Data

The data come from the first wave of the Costa Rican Study on Longevity and Healthy Aging (CRELES) and the second wave of the Social Environment and Biomarkers of Aging Study (SEBAS). In both surveys, an interview conducted in the respondent's home included questions related to health and a series of performance-based assessments. SEBAS and CRELES included informed consent from all participants and received ethical approval from the human subjects committees at the institutions conducting the studies.

CRELES is a longitudinal study based on a national sample of residents of Costa Rica aged 60 and older in 2005, with oversampling of the oldest old (Rosero-Bixby, Fernández, & Dow, 2010). The sample was selected randomly from the 2000 census database using a multi-stage sampling design. For this analysis, we use data from the first wave conducted between November 2004 and September 2006. Interviews were completed by 2827 respondents (85% of located survivors).

The SEBAS cohort represents a random subsample of participants in the nationally representative Taiwan Longitudinal Study of Aging (TLSA); elderly persons and urban residents were oversampled. TLSA began in 1989 and younger refresher cohorts were added in 1996 and 2003; all three cohorts were selected randomly using a multi-stage sampling design. The sampling frame for the 2006 SEBAS included: a) an older cohort (aged 60+) of respondents from the 1999 wave of TLSA who completed the 2000 SEBAS medical examination, and b) a younger cohort (aged 53-60) of respondents first interviewed in the 2003 wave of TLSA. Interviews were completed by 1284 respondents aged 53 and older in 2006 (87% response rate). Additional details are provided elsewhere (Chang et al., 2012).

Measures

Mortality

For SEBAS, survival status as of June 30, 2011 was ascertained through linkage with the death certificate file maintained by the Department of Health and the household registration database maintained by the Ministry of the Interior. Survival status in CRELES was established in two ways: (1) through the computer records in the National Death Registry up to December 31, 2010, and (2) during the second and third waves of home visits. The computer follow-up used the unique identification number (the *cédula*) that all Costa Ricans have. Five out of the 566 deaths found in the field were not found in the Registry, suggesting a death under-registration rate of 1%. In contrast, 10% of the deaths from the Registry were not found in the field, appearing in the second and third waves as loss of follow-up. For the foreigners in the sample (approx. 3%), survival was established only in the field because they did not have a unique identification number with which to link them to the Registry.

Measures of Physical Function

We include two self-reported measures of physical function: number of limitations with activities of daily living (ADL) limitations (0-5) and number of mobility limitations (0-4; see footnotes to Table 1 for specific activities). Four health assessments were administered by trained interviewers: grip strength, PEF, timed walk, and chair stands (see Supplementary Material for details).

Potential Confounders

Factors considered as potential confounders include age, sex, education, and urban residence. In auxiliary analyses, we also control for self-reported measures of specific health conditions (i.e., cancer, heart disease, diabetes, stroke, respiratory disease, arthritis, hypertension); smoking status (never, former, current); exercise (3+ times per week); and hospitalization in the past year.

Analytical Strategy

Among those interviewed, 6.1% of the CRELES sample and 5.1% of the SEBAS sample are missing data for a measure of physical function, either self-reported (*n*=14 in CRELES; *n*=6 in SEBAS) or performance-based (*n*=160 in CRELES; *n*=59 in SEBAS). Exclusion of these respondents leaves an analysis sample of 2653 for Costa Rica and 1219 for Taiwan.

Descriptive statistics are weighted to account for oversampling and for differential response rates by age, sex, and other covariates. Survival models are fit separately by country using unweighted data. We estimate age-specific mortality using a Gompertz proportional hazards model with time measured in terms of age. Initial tests (not shown) showed no significant evidence that the age slope of mortality (γ) varied by sex in these samples.

Some of the performance tests are strongly correlated with one another (e.g., among those with measurements, the Pearson correlations between grip strength and PEF are 0.60 in CRELES and 0.65 in SEBAS, and correlations between walking speed and chair stand speed are 0.37 in CRELES and 0.51 in SEBAS). Thus, we model the performance assessments individually as well as jointly. To assess the prognostic value of the performance assessments over and above that of the self-reported measures of physical function, we first estimate a model that includes only self-reported ADL and mobility limitations in addition to sociodemographic confounders. Subsequent models include those variables along with a categorical specification for performance tests: those unable to perform a given test are assigned a separate category, and the remaining responses are recoded into quartiles based on the weighted distribution of the pooled samples.

To evaluate the predictive ability of different measures of physical function, we compare the model-based predicted probability of dying by the end of follow-up (see Supplementary Material for details) with the observed binary outcome (death vs. survival) to estimate the area under the receiver-operating-characteristic (ROC) curve (AUC). We use the “rocgold” procedure in Stata 12.1 to test whether the addition of performance assessments yields a significant improvement in mortality prediction. Similarly, we compare the AUC from models that include individual performance tests to determine whether some assessments are better predictors than others. We present both the absolute increase in AUC between pairs of nested models as well as the increase in AUC for a given model as a percentage of the area above the curve (i.e., (1-AUC) or the fraction of incorrect predictions) for the simpler model.

Finally, to help gauge the magnitude of the association with mortality, we calculate the predicted probability of dying between exact ages 70 and 75 (${}_5\hat{q}_{70}$) for selected levels of performance. These probabilities are estimated by setting the selected performance assessment at the specified value, fixing all other covariates at the weighted mean for the pooled sample, and using the model coefficients to predict the probability of dying between exact ages 70 and 75 (see Supplementary Material for details). For each performance test, we provide two sets of predicted probabilities. The first is based on a model that includes only the selected performance assessment and sociodemographic controls, thus representing the "gross effect" without adjusting for any other measures of physical function. The second is based on a model that includes all physical function measures (both self-reported and performance-based) in addition to control variables and thus, represents the "net effect" after adjusting for the effects of all other measures of physical function.

RESULTS

In CRELES, there were 700 deaths by January 1, 2011; the average length of mortality follow-up was 5.2 years (max, 6.2 years). For SEBAS, there were 140 deaths by June 30, 2011; mean follow-up was 4.7 years (max, 4.9 years). The Costa Rican sample is older than the Taiwanese sample (Table 1), reflecting differences in the sampled population (60+ for CRELES, 53+ for SEBAS). Relatively few respondents report any of the five ADL limitations (12% in Costa Rica, 7% in Taiwan), but a greater proportion report at least one of the four mobility limitations (59% in Costa Rica; 37% in Taiwan; not shown).

In the hazard models that include only self-reported measures (Model 1, Tables 2 and 3), mobility limitations are associated with higher mortality rates in both Costa Rica (HR=1.29, p<0.001) and Taiwan (HR=1.50, p<0.001), but ADL limitations are significant only in Costa Rica (HR=1.21, p<0.001). In models that add a single performance test (Models 2a-2d), joint Wald chi-square tests (based on the four parameters for a given assessment) indicate that each of the four performance tests is significantly associated with mortality in Costa Rica, but only grip strength and PEF are significantly associated with mortality in Taiwan. The fact that the sample size in Costa Rica is more than twice that in Taiwan accounts for the significance of some estimates for Costa Rica even when the magnitudes of the hazard ratios are similar to or smaller than the corresponding values in Taiwan.

The hazard ratios are substantially attenuated when all performance tests are included in a single model (Model 5, Tables 2 and 3). Grip strength and PEF continue to be significantly related to mortality in both countries, but walking speed and chair stand speed are not. Being unable to perform the PEF test is a particularly strong predictor of mortality (HR=2.7 in Costa Rica; HR=5.2 in Taiwan relative to those in the top quartile). Poor PEF performance (bottom quartile) also strongly predicts mortality in both countries (HRs>2). In addition to the models presented in Tables 2 and 3, we estimated an auxiliary model that includes controls for specific health conditions, smoking, exercise, and hospitalization. Although the coefficients for PEF weaken slightly with the inclusion of these variables, both PEF and grip strength remain strong predictors of mortality (results not shown).

Comparisons of the AUC for different models show that self-reported measures of physical function yield a substantial and significant improvement in mortality prediction compared with a baseline model that adjusts only for sociodemographic characteristics—the increase in AUC is greater than 10% of the area above the curve (1-AUC) for the baseline model in both countries (Table 4). Beyond the prognostic value of self-reported physical function, only one of the performance assessments, PEF, provides a significant improvement in predictive ability in both countries. Grip strength and walking speed produce smaller improvements that are significant only in Costa Rica.

A ranking of the four assessments in terms of the absolute increment in AUC results in the following order of performance measures, from largest to smallest: PEF, grip strength (tied with walking speed in Costa Rica), walking speed, and chair stands. This ordering is used to evaluate whether successive additions of assessments provide significant and substantial improvements in mortality prediction. Based on the criterion of 0.01 to indicate a meaningful improvement in the AUC (Pencina, D'Agostino, D'Agostino, & Vasan, 2008), PEF appears to be a useful measure (the gain in AUC equaled 0.015 in Taiwan and was just below 0.01 in Costa Rica). Compared with PEF alone (Model 2b), the addition of grip strength (Model 3a) yields a small but significant increase in AUC in Costa Rica (0.004), whereas the gain in Taiwan is larger (0.010) but not significant. The addition of walking speed to PEF (Model 3b) leads to increases in AUC of a similar magnitude as the addition of grip strength (Model 3a), but the increases for walking speed are significant in both data sets. The addition of chair stand speed to any of the models in Table 4 results in more modest increases in AUC.

Table 5 shows the extent of variation in the predicted probability of dying between exact ages 70 and 75 (${}_{5}\hat{q}_{70}$) by selected levels of performance on the physical assessments. Differences are particularly large for grip strength and PEF. For example, the gross effect for PEF (i.e., before adjusting for the effects of other measures of physical function) suggests that 26% of Costa Ricans who were unable to perform the test would be expected to die between ages 70 and 75 compared with only 6% of those in the top quartile; corresponding figures for Taiwan are 37% vs. 4%. After adjustment for the contribution of other physical function measures, the net effect for PEF is smaller, but remains substantial (Costa Rica: 17% of unable vs. 7% in the top quartile; Taiwan: 22% vs. 5%, respectively). Some of the differences are large even without consideration of those unable to complete the tests. For example, in both countries, the net effect of PEF on mortality is twice as high for those in the bottom quartile compared with the top quartile.

Additional models (not shown) explore variations in the association between performance-based assessments and mortality by three potential modifiers: age (<70 vs. 70+), sex, and self-reported limitations (any vs. none). All models include the basic sociodemographic confounders. In the first set of models, 12 for each country, we examine only one set of interaction terms in each model: we include interaction terms between one of the four performance assessments and one of the three modifying variables, along with the corresponding main effects. Joint tests for the set of interaction terms are significant in only 3 of 24 tests, slightly more than we would expect by chance. In a second set of 3 models for each country, we include all measures of physical function (self-reported and performance-based) along with interaction terms between the full set of performance assessments and a given modifying variable. None of the joint tests attain statistical significance. Thus, we find little evidence that the prognostic value of the performance tests varies by age, sex or the presence of self-reported limitations.

DISCUSSION

Health interview surveys routinely ask respondents about their physical limitations, but they are much less likely to measure respondents' physical performance with trained observers, presumably because of the expense, complex logistics, and burden for participants. Since it is easier to obtain self-reports than to administer performance tasks, it is important to ascertain the additional value derived from such tests. Of course, their value depends in large part on the particular questions being addressed. In this analysis, we consider the prognostic value of four types of performance tests over and above self-reported limitations for five-year mortality.

The paucity of previous studies addressing this issue, combined with variability across data sets in the measures collected, has yielded few robust findings. One study suggested that the chair stand test provided the strongest mortality prediction (Cesari et al., 2008), while other work favored walking speed (Al Snih et al., 2002; Markides et al., 2001) and another study reported that grip strength had the biggest effect in women and PEF had the biggest effect in men (Rosero-Bixby & Dow, 2012). None of these prior studies included all four performance tests. Our findings, which are remarkably similar in Taiwan and Costa Rica, reveal that for both countries—in the presence of controls for self-reported ADL and mobility limitations—PEF has the strongest association with mortality. In models that include all four assessments, PEF and grip strength measures significantly predict mortality, whereas chair stand and walking speed do not. The discrepancies between our results and previous findings are likely owing to two factors. One relates to the batteries of tests used in the earlier studies: chair stands and walking speed were generally included, whereas grip strength and PEF were not. A second explanation is that previous studies controlled for self-reported (ADL)limitations, but not mobility limitations. Tabulations (not shown) indicated that, when we omitted controls for self-reported limitations, the advantage of PEF and grip strength relative to the other two performance tasks was diminished, particularly in Costa Rica. This result is not surprising since ADL limitations, mobility limitations, chair stand speed, and walking speed all reflect lower extremity function.

Are the performance tests sufficiently strong predictors of mortality to warrant their inclusion in household surveys? Our results indicate that PEF and grip strength (and gait speed in Costa Rica) yield sizeable improvements in mortality prediction above and beyond self-reported limitations; the gains in prediction are stronger in Taiwan than in Costa Rica, but, because of the smaller sample size, are less likely to be statistically significant in Taiwan.

Many studies have examined the links between PEF or grip strength and mortality (although only a few have done so in conjunction with other performance tests and self-reported limitations). Most have found strong and robust associations between each of these two performance tasks and all-cause mortality (Cook et al., 1991; Cooper et al., 2010; Rosero-Bixby & Dow, 2012; Simons et al., 2011; Vaz Fragoso, Gahbauer, Van Ness, Concato, & Gill, 2008). Although explanations for these strong links remain unclear (Gale, Martyn, Cooper, & Sayer, 2007; Schrack, Simonsick, & Ferrucci, 2010), multiple mechanisms are likely to be involved. Rantanen et al. (2003) argue that grip strength, which indicates overall muscle strength, predicts survival not only because of chronic diseases that result in muscle impairment through nutritional deficiency, inflammation, physical inactivity, and depression. Even in the absence of recognizable disease, weak muscle strength may reflect inactivity and disability, which increase susceptibility to injury and can compromise subsequent healing (Rantanen et al., 2003). It could also reflect early life nutrition and fetal development (Gale et al., 2007; Rantanen et al., 2003) or be a marker of subclinical disease (Rantanen et al., 2003). Similarly, Vaz Fragoso et al. (2008) suggest that a diminished PEF reflects more than chronic lung disease or exposure to smoke or pollution; for example, low PEF may indicate impaired respiratory muscle strength, upper-extremity functional limitations, and poor cognitive function. Both PEF and grip strength are thought to capture a person's overall vigor or vitality (Cook et al., 1991). Both measures also have some clear advantages as risk assessment tools in household surveys, particularly in developing countries: unlike chair stands, there is no need to adjust for differences in chair size;

in contrast to the timed walk, they do not require unobstructed space; and there is no need to time performance, which may increase measurement error.

A limitation of this study – as with any application of performance tasks – is that some respondents are unwilling, unable, or excluded from participation because of health and safety concerns. This proportion is much lower for grip strength (5% in SEBAS; 11% in CRELES) than for chair stands (12% and 27%, respectively). As indicated by the hazard ratios in Table 3, being unable to perform a test (including those excluded for health reasons) is often a strong predictor of impending death. However, these indicators are not well-defined: exclusion rates vary by the specific task and are likely to depend on the underlying demographic, health, social and cultural characteristics of the sample. They are also likely to differ by the degree of caution and safety concerns of the survey investigators, thereby generating variability across surveys in the strength of the association between these variables and health status.

Few researchers question the importance of collecting self-reported data on physical limitations in older populations. In this study we demonstrate the utility of performance assessments, even when high quality self-reported measures are available. Nonetheless, our findings indicate that it may not be necessary or cost effective to collect a large battery of performance tests, in part because of substantial correlations among the tasks. For predicting mortality—at least within a five-year period—measurements of PEF and grip strength may suffice. Although our findings are reinforced by the consistency of estimates for Costa Rica and Taiwan, future work should examine the robustness of these results to different settings and populations. With the recent expansion of data collection in longitudinal household surveys, future analyses should also assess the predictive power of *changes* in performance between survey waves, which may enhance models of health and survival beyond what can ascertained from cross-sectional measures. They may also add prognostic value to models that include changes in self-reported health and functional ability as well as changes in physiological markers (e.g., biomarkers of the cardiovascular or immune system).

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Table 1. Descriptive statistics for all analysis variables, by country, weighted analyses

	Costa Rica [CRELES] (n=2653)	**Taiwan [SEBAS]** (n=1219)
Sociodemographic characteristics		
Age at the time of the survey, mean (SD)	70.9 (8.1)	65.9 (9.2)
Female, %	52.4	46.1
Urban resident, %	62.3	47.4
Years of completed education (0-17), mean (SD)	5.2 (4.2)	6.6 (4.7)
Self-reported measures of physical function		
Number of ADL limitations (0-5), mean (SD)[a]	0.3 (1.0)	0.2 (0.9)
Number of mobility limitations (0-4), mean (SD)[b]	1.3 (1.3)	0.7 (1.1)
Performance-based measures of physical function		
Unable to perform grip strength test, %	3.1	3.4
Grip strength (kg), mean (SD)[c,d]	26.9 (9.1)	28.2 (10.6)
Unable to perform PEF test, %	9.6	3.5
PEF (L/min), mean (SD)[c,e]	310.2 (120.1)	334.5 (135.7)
Unable to perform timed walk, %	9.3	4.2
Walking speed (m/sec), mean (SD)[c,f]	0.6 (0.2)	0.9 (0.3)
Unable to perform chair stands test, %	12.8	8.4
Chair stand speed (stand/sec), mean (SD)[c]	0.4 (0.1)	0.5 (0.2)
Died by the end of followup[g], %	10.5	16.8

ADL, Activities of Daily Living; PEF, peak expiratory flow

[a] Based on five ADLs (bathing; eating; toileting; moving around the house; getting out of bed), we counted the number of ADLs that the respondent reported difficulty performing.

[b] A count of the number of mobility tasks that the respondent reported difficulty performing. Three of the four mobility tasks were similar in both countries (i.e., walking; climbing stairs; raising his/her arms). In Costa Rica, respondents were asked to demonstrate whether they could lift their arms above their shoulders; those who did not attempt the test are coded as having difficulty. In Taiwan, difficulty raising both hands overhead was based on self-report. The fourth task differed between Costa Rica (i.e., pushing or pulling a large object such as a recliner chair) and Taiwan (i.e., lifting or carrying 11-12 kgs). In Costa Rica, respondents who reported that they "do not do that activity" were coded as having difficulty.

[c] Among those able to complete the test.

[d] Maximum from trials on both hands except for *n*=10 in CRELES and *n*=50 in SEBAS who did not complete trials on both hands.

[e] Maximum from three trials except for *n*=8 in CRELES and *n*=14 in SEBAS who completed only one or two trials.

[f] In SEBAS, *n*=12 walked only 2-2.5m because of space limitations in the respondent's home; walking speed was calculated based on the distance actually walked.

[g] Followup ended on January 1, 2011 for CRELES and June 30, 2011 for SEBAS. In CRELES, a few foreigners (*n*=60) were censored early, at the date of last contact. The unweighted number of deaths was 700 in CRELES and 140 in SEBAS.

Table 2. Hazard ratios from Gompertz model of age-specific mortality[a], Costa Rica (n=2653)

	(1)	(2a)	(2b)	(2c)	(2d)	(5)
Self-reported measures						
ADL limitations	1.21***	1.20***	1.18***	1.18***	1.17***	1.17***
Mobility limitations	1.29***	1.24***	1.24***	1.22***	1.23***	1.16***
Performance-based tests						
Grip strength (kg)						
Unable to perform test		2.20***				1.50
Bottom quartile (2-20)		2.21***				1.64*
2nd quartile (20.1-26)		1.42				1.15
3rd quartile (26.5-34)		1.53*				1.39
Top quartile (34.5-68)		(ref)				(ref)
Joint test[b] (*df* = 4)		*p*<0.001				*p*~0.016
PEF (L/min)						
Unable to perform test			3.15***			2.70***
Bottom quartile (50-230)			2.56***			2.17***
2nd quartile (235-300)			1.67*			1.50
3rd quartile (310-390)			1.68*			1.62*
Top quartile (400-800)			(ref)			(ref)
Joint test[b] (*df* = 4)			*p*<0.001			*p*<0.001
Walking speed (m/sec)						
Unable to perform test				2.12*		1.33
Bottom quartile (0.06-0.52)				1.95*		1.58
2nd quartile (0.52-0.66)				1.49		1.35
3rd quartile (0.66-0.83)				1.13		1.05
Top quartile (0.83-2.14)				(ref)		(ref)
Joint test[b] (*df* = 4)				*p*~0.002		*p*~0.095
Chair stand speed (stands/sec)						
Unable to perform test					1.85**	1.38
Bottom quartile (0.09-0.34)					1.49	1.10
2nd quartile (0.34-0.42)					1.12	0.94
3rd quartile (0.42-0.52)					1.24	1.14
Top quartile (0.52-1.98)					(ref)	(ref)
Joint test[b] (*df* = 4)					*p*~0.007	*p*~0.267

*** $p<0.001$, ** $p<0.01$, * $p<0.05$

[a] All models control for sex, education, and urban residence.

[b] Joint Wald chi-square test for the four parameters pertaining to specified assessment.

Table 3. Hazard ratios from Gompertz model of age-specific mortality[a], Taiwan (n=1219)

	(1)	(2a)	(2b)	(2c)	(2d)	(5)
<u>Self-reported measures</u>						
ADL limitations	1.11	1.07	1.04	1.02	1.08	1.04
Mobility limitations	1.50***	1.37***	1.39***	1.46***	1.40***	1.31**
<u>Performance-based tests</u>						
Grip strength (kg)						
Unable to perform test		3.15*				1.00
Bottom quartile (2-20)		3.36**				2.50*
2nd quartile (20.1-26)		2.13*				1.61
3rd quartile (26.5-34)		1.42				1.24
Top quartile (34.5-68)		(ref)				(ref)
Joint test[b] (*df* = 4)		*p*~0.011				*p*~0.049
PEF (L/min)						
Unable to perform test			5.17***			5.15**
Bottom quartile (50-230)			2.93**			2.22*
2nd quartile (235-300)			2.99**			2.32*
3rd quartile (310-390)			2.10*			1.94
Top quartile (400-800)			(ref)			(ref)
Joint test[b] (*df* = 4)			*p*~0.004			*p*~0.029
Walking speed (m/sec)						
Unable to perform test				2.17		1.35
Bottom quartile (0.06-0.52)				1.48		0.97
2nd quartile (0.52-0.66)				0.79		0.56
3rd quartile (0.66-0.83)				1.51		1.18
Top quartile (0.83-2.14)				(ref)		(ref)
Joint test[b] (*df* = 4)				*p*~0.079		*p*~0.187
Chair stand speed (stands/sec)						
Unable to perform test					2.14*	1.29
Bottom quartile (0.09-0.34)					1.58	1.23
2nd quartile (0.34-0.42)					1.42	1.13
3rd quartile (0.42-0.52)					1.75	1.51
Top quartile (0.52-1.98)					(ref)	(ref)
Joint test[b] (*df* = 4)					*p*<0.262	*p*~0.721

*** $p<0.001$, ** $p<0.01$, * $p<0.05$

[a] All models control for sex, education, and urban residence.

[b] Joint Wald chi-square test for the four parameters pertaining to specified assessment.

Table 4. Comparisons of the AUC for various models, by country

			Costa Rica			Taiwan		
		Comparison	AUC	Δ in AUC[a]	Δ as a % of unexplained[b]	AUC	Δ in AUC[a]	Δ as a % of unexplained[b]
0	Baseline model (control variables only)		0.776			0.773		
1	Add self-reported physical function[c]	vs. Model 0	0.808	0.032***	14%	0.800	0.027**	12%
2a	Model 1 + grip strength	vs. Model 1	0.813	0.005*	3%	0.813	0.013	6%
2b	Model 1 + PEF	vs. Model 1	0.816	0.008*	4%	0.815	0.015*	7%
2c	Model 1 + walking speed	vs. Model 1	0.813	0.005*	3%	0.809	0.009	5%
2d	Model 1 + chair stand speed	vs. Model 1	0.812	0.004	2%	0.805	0.005	3%
3a	Model 1 + (PEF, grip strength)	vs. Model 2b	0.820	0.004*	2%	0.825	0.010	5%
3b	Model 1 + (PEF, walking speed)	vs. Model 2b	0.820	0.004*	2%	0.823	0.008*	4%
3c	Model 1 + (PEF, chair stand speed)	vs. Model 2b	0.819	0.003*	2%	0.819	0.004	2%
4a	Model 1 + (PEF, grip strength, walking speed)	vs. Model 3a	0.823	0.003	1%	0.832	0.007	4%
4b	Model 1 + (PEF, grip strength, chair stand speed)	vs. Model 3a	0.822	0.002	1%	0.828	0.003	1%
4c	Model 1 + (PEF, walking speed, chair stand speed)	vs. Model 3b	0.821	0.002	1%	0.825	0.002	1%
5	Model 1 + all four performance tests[d]	vs. Model 4a	0.824	0.001	1%	0.834	0.002	1%

*** $p<0.001$, ** $p<0.01$, * $p<0.05$

[a] The change (Δ) in the AUC and associated significance level is based on a comparison with the model indicated.

[b] The Δ in the AUC as a percent of unexplained is computed as: $\frac{AUC^{\text{Model } Y} - AUC^{\text{Model } X}}{(1 - AUC^{\text{Model } X})}$, where Model X is the current model and Model Y is the comparison model.

[c] This model is the same as Model 1 presented in Tables 2 and 3.

[d] This model is the same as Model 5 presented in Tables 2 and 3.

Table 5. Predicted probability of dying between age 70 and 75 ($_5\hat{q}_{70}$) for selected levels of performance on the physical assessments[a], by country

	Gross effect[b]		**Net effect[c]**	
	Costa Rica	Taiwan	Costa Rica	Taiwan
Observed $_5q_{70}$ in the national population[d]				
Total	0.103	0.123		
Men	0.125	0.154		
Women	0.082	0.095		
Performance-based tests				
Grip strength				
Unable	0.31	0.29	0.12	0.06
Bottom quartile (2-20 kg)	0.20	0.19	0.13	0.15
Top quartile (34.5-68 kg)	0.07	0.04	0.08	0.06
PEF				
Unable	0.26	0.37	0.17	0.22
Bottom quartile (50-230 L/min)	0.18	0.15	0.14	0.10
Top quartile (400-800 L/min)	0.06	0.04	0.07	0.05
Walking speed				
Unable	0.29	0.34	0.11	0.13
Bottom quartile (0.06-0.52 m/sec)	0.16	0.18	0.13	0.09
Top quartile (0.83-2.14 m/sec)	0.07	0.07	0.09	0.10
Chair stand speed				
Unable	0.27	0.28	0.13	0.10
Bottom quartile (0.09-0.34 stands/sec)	0.14	0.14	0.11	0.09
Top quartile (0.52-1.98 stands/sec)	0.08	0.06	0.10	0.08

[a] All models control for sex, age, education, and urban residence. The predicted probabilities of dying between exact ages 70 and 75 are estimated by setting the selected measure of physical function at the specified value and fixing all other covariates at the weighted mean for the pooled sample.

[b] We fit a separate model for each performance test and adjust only for sociodemographic control variables.

[c] We fit a model that includes all measures of physical function (both self-reported and performance-based) in addition to control variables (same as Model 2, Table 2).

[d] The observed $_5q_{70}$ is based on the period life table for 2007. Estimates for Taiwan come from the Human Mortality Database (www.mortality.org, accessed November 22, 2011; (Human Mortality Database (HMD), 2011)). Estimates for Costa Rica come from the 2007 life table on the Centro Centroamericano de Población web site (http://ccp.ucr.ac.cr/observa/CRindicadores/tv70_09.html, accessed on 19 July 2012).

SUPPLEMENTARY MATERIAL

MEASURES

Performance-Based Physical Function

Grip Strength

Grip strength (in kg) was measured using a dynamometer (CRELES: Creative Health Products dynamometer [model T-18]; SEBAS: North Coast™ hydraulic hand dynamometer [NC70142]); we used the highest level from several trials: two trials on the dominant hand in CRELES and three trials on each hand in SEBAS. The respondent was coded as "unable" to perform the test if s/he: a) met the exclusion criteria for both hands; b) tried but was unable to do the test; c) did not attempt the test for safety reasons; d) [in CRELES only] was not tested because of disability; e) [in SEBAS only] did not attempt the test because of weakness, stroke, or frailty or stopped because of pain or discomfort. The exclusion criteria included: surgery on hand/wrist/arm in the past three months and [in SEBAS only] recent injury, worsening pain, swelling, inflammation, or severe pain in the hand/wrist. The test was coded as missing if the respondent refused [or in the case of SEBAS, was unable to understand the instructions].

Peak expiratory flow (PEF)

Lung function, represented by PEF (L/min), was based on the maximum of three trials using a peak flow meter (CRELES: Mini Wright; SEBAS: TruZone®). In CRELES, the "unable" group included respondents who were unable to complete even one trial. In SEBAS, the respondent was coded as "unable" if: a) s/he met the exclusion criteria (i.e., surgery on chest/abdomen or hospitalized for a heart problem in the past six weeks; detached retina or eye surgery in past six months; hospitalized for respiratory or lung infection in past three weeks), b) s/he did not attempt the test because of stroke or illness, or c) s/he or the interviewer felt it was unsafe. The test was coded as missing if the respondent refused [or in the case of SEBAS, was unable to understand the instructions or there was equipment failure].

Walking speed

To measure walking speed (m/sec), the respondents were asked to walk three meters at their normal speed. The respondent started from a sitting position in CRELES; s/he started from a standing position in SEBAS. CRELES included one trial; SEBAS conducted two trials (we used the faster of the two). The respondent was coded as "unable" to complete the test if s/he: a) tried but was unable to do the test; b) did not attempt the test for safety reasons; or c) [in CRELES only] reported any problem that would impair him/her from doing a mobility and flexibility test. Data were coded as missing if the respondent refused [or, in the case of SEBAS, was unable to understand the instructions].

Chair stands

For the chair stand test, the respondent was asked to stand up and sit down again five times in a row as quickly as possible without stopping while keeping his/her arms folded across his/her chest. For those able to complete five stands, the completion time was recorded. To adjust for differences in chair height, we regressed the completion time (c_i) for individual i on chair height (h_i) controlling for the respondent's age and height [SEBAS]/knee height [CRELES], with models fit separately by sex [1]. The adjusted completion time was calculated as $\tilde{c}_i = c_i + \beta_s(\bar{h} - h_i)$, where β_s was the coefficient for h_i from the sex-specific model and $\bar{h}$ was the mean chair height among the pooled sample (44.5 cm). Chair stand speed was computed as five divided by the adjusted time $\tilde{c}_i$. The respondent was coded as "unable" to perform the test if s/he: a) met the exclusion criteria (CRELES: reported any problem that would impair him/her from doing a mobility and flexibility test; SEBAS: was in a wheelchair); b) tried but was unable to do the test, or c) did not attempt the test for safety reasons. The test was coded as missing for those who refused [or, in the case of SEBAS, were unable to understand the instructions or there was no suitable chair for the test].

PREDICTED PROBABILITY OF DYING BY THE END OF FOLLOW-UP

To calculate the AUC using ROC analysis, we use the model coefficients to compute the predicted probability of dying by the end of follow-up for each respondent, which is then compared with the observed outcome (i.e., whether or not a given respondent actually died by the end of follow-up). Follow-up ended on January 1, 2011, in the CRELES and on June 30, 2011, in the SEBAS. For a few respondents who were censored early, we calculate the predicted probability of dying by the date of censorship, which corresponds with the observed outcome (survival status at the time of censorship; we do not know the respondent's vital status at the end of the follow-up period).

The Gompertz model takes the following form:

$$\ln \boldsymbol{h}(\boldsymbol{t}_j) = \gamma \boldsymbol{t}_j + \boldsymbol{x}_j \beta \ , \tag{1}$$

where $\boldsymbol{t}_j$ represents time measured in age for individual $\boldsymbol{j}$, $\boldsymbol{h}(\boldsymbol{t}_j)$ is the hazard rate at time $\boldsymbol{t}_j$, γ denotes the age slope, $\boldsymbol{x}_j$ represents the vector of covariates, and $\boldsymbol{\beta}$ is the corresponding vector of regression coefficients. We calculate the linear prediction ($\boldsymbol{x}_j\boldsymbol{\beta}$) for each respondent using the observed values for the covariates and the coefficients from the model. We then use the estimate of γ from the model to calculate the conditional probability of surviving from the date of the survey ($\boldsymbol{t}_j^{Survey}$) to the end of follow-up ($\boldsymbol{t}_j^{End}$):

$$\hat{\boldsymbol{S}}\left(\boldsymbol{t}_j^{Survey}, \boldsymbol{t}_j^{End}\right) = \frac{\hat{\boldsymbol{S}}\left(\boldsymbol{t}_j^{End}\right)}{\hat{\boldsymbol{S}}\left(\boldsymbol{t}_j^{Survey}\right)} \ , \tag{2}$$

where the survival function for the Gompertz model is:

$$\boldsymbol{S}(\boldsymbol{t}) = \exp\left\{\frac{\mathrm{e}^{\boldsymbol{x}\beta}\left(1 - \mathrm{e}^{\gamma \boldsymbol{t}}\right)}{\gamma}\right\} \ . \tag{3}$$

Finally, we calculate the probability of dying:

$$\hat{\boldsymbol{q}}\left(\boldsymbol{t}_j^{Survey}, \boldsymbol{t}_j^{End}\right) = 1 - \hat{\boldsymbol{S}}\left(\boldsymbol{t}_j^{Survey}, \boldsymbol{t}_j^{End}\right) \ . \tag{4}$$

PREDICTED PROBABILITY OF DYING BETWEEN AGE 70 AND 75 (${}_{5}\hat{q}_{70}$)

These probabilities are estimated by setting the selected performance assessment at the specified value, fixing all other covariates at the weighted mean for the pooled sample, and using the model coefficients to predict the probability of dying between exact ages 70 and 75. This age interval corresponds roughly to the mean age at the time of the survey (69.3) and at the end of follow-up (74.3) for the pooled sample (weighted). Thus, the predicted probability of dying between age 70 and 75 is computed as:

$$ {}_{5}\hat{\boldsymbol{q}}_{70} = 1 - \boldsymbol{S}(70,75) \, , \qquad (5) $$

where the conditional probability of surviving from age 70 to 75 is:

$$ \boldsymbol{S}(70,75) = \frac{\boldsymbol{S}(75)}{\boldsymbol{S}(70)} \, , \qquad (6) $$

and $\boldsymbol{S}(\boldsymbol{t})$ is calculated using the formula given in Eq. (3) with the selected measure of physical function set at a specified value and the remaining covariates fixed at the weighted mean for the pooled sample.

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