Comparison of alternate scoring of variables on the performance of the frailty index

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Abstract

Background: The frailty index (FI) is used to measure the health status of ageing individuals. An FI is constructed as the proportion of deficits present in an individual out of the total number of age-related health variables considered. The purpose of this study was to systematically assess whether dichotomizing deficits included in an FI affects the information value of the whole index.

Methods: Secondary analysis of three population-based longitudinal studies of community dwelling individuals: Nova Scotia Health Survey (NSHS, n = 3227 aged 18+), Survey of Health, Ageing and Retirement in Europe (SHARE, n = 37546 aged 50+), and Yale Precipitating Events Project (Yale-PEP, n = 754 aged 70+). For each dataset, we constructed two FIs from baseline data using the deficit accumulation approach. In each dataset, both FIs included the same variables (23 in NSHS, 70 in SHARE, 33 in Yale-PEP). One FI was constructed with only dichotomous values (marking presence or absence of a deficit); in the other FI, as many variables as possible were coded as ordinal (graded severity of a deficit). Participants in each study were followed for different durations (NSHS: 10 years, SHARE: 5 years, Yale PEP: 12 years).

Results: Within each dataset, the difference in mean scores between the ordinal and dichotomous-only FIs ranged from 0 to 1.5 deficits. Their ability to predict mortality was identical; their absolute difference in area under the ROC curve ranged from 0.00 to 0.02, and their absolute difference between Cox Hazard Ratios ranged from 0.001 to 0.009.

Conclusions: Analyses from three diverse datasets suggest that variables included in an FI can be coded either as dichotomous or ordinal, with negligible impact on the performance of the index in predicting mortality.

Keywords: Aging, Frailty index, Deficit accumulation, Coding

Background

As individuals age, their vulnerability to adverse outcomes (including death) increases. Some individuals experience a state of increased vulnerability, known as frailty, which can be quantified using a frailty index [1]. The frailty index, introduced more than a decade ago [2], is a useful tool for assessing the health status of individuals, and for predicting an individual’s risk of adverse health outcomes [3,4]. Following a standard procedure, a frailty index can be constructed as the proportion of age-related health deficits an individual has accumulated [5]. Deficits can be any diseases, signs, symptoms, laboratory abnormalities, or functional or cognitive impairments, as long as about 30 measures are included which comprise a range of physiological systems. The more deficits one has, the higher their frailty index and the more vulnerable they are to adverse outcomes. Frailty indices demonstrate similar characteristics across diverse samples and settings, even when they employ different variables or different numbers of variables [1]. For example, frailty index values consistently increase with age, are strongly associated with mortality, and show higher values in women than in men.

Searle et al. [5] proposed criteria for selecting and coding health measures for inclusion as variables in a frailty index: deficits should be age-related, associated with adverse outcomes, contain little missing data (a 5% threshold was proposed) and not saturate with age (i.e. was
not present in most people by some age, typically operationalized as being present in >80% of people by age 80). Searle and colleagues suggested that each variable included in a frailty index should be mapped to a 0 to 1 interval, assigned a value of 0 when a deficit is absent and 1 when it is fully expressed. It is not known, however, whether continuous or ordinal variables should be transformed into the dichotomous 0 and 1 values, or whether intermediate ordinal scores (e.g. self-rated health of “good” or “fair”), should be assigned intermediate values (e.g. 0.25 or 0.5). It is possible that by converting continuous variables (e.g. blood pressure) into dichotomous variables (e.g. “hypertension” present/absent), important information might be lost. The purpose of this study was to systematically assess whether dichotomizing deficits included in a frailty index affects the information value of the whole index. Within each of three large datasets with different settings and different durations of follow-up, we compared two different frailty indices using the same variables, but differing in whether the variables were dichotomized or categorized as ordinal variables. Specifically, we assessed for significant differences between: 1. descriptive characteristics of each frailty index, and; 2. its predictive validity using mortality as the primary outcome.

Methods
This is a secondary analysis of three longitudinal studies: the Nova Scotia Health Survey (NSHS), the Survey of Health, Ageing and Retirement in Europe (SHARE), and the Yale Precipitating Events Project (Yale-PEP).

Nova Scotia health survey
The Nova Scotia Health Survey began in 1995 and employed a representative probability sample designed by Statistics Canada. The sample included 3227 non-institutionalized Nova Scotians aged 18-99 (mean age = 48.1, SD = 19.8). There were approximately equal number of men and women in the sample (women n = 1618, 50.1%). Demographic, anthropometric, lifestyle, and risk factor data were collected at baseline and mortality data were obtained via linkage with the National Vital Statistics database 10 years following the baseline assessment. Full details of the data collection are presented elsewhere [6].

Table 1 Coding of variables for the Nova Scotia Health Survey

| Variable name                        | Ordinal response/code | Dichotomous response/code |
|--------------------------------------|-----------------------|---------------------------|
| Arthritis/Rheumatism                 | no = 0, yes = 1       | no = 0, yes = 1           |
| Back problems                       | no = 0, yes = 1       | no = 0, yes = 1           |
| Osteoporosis                         | no = 0, yes = 1       | no = 0, yes = 1           |
| Chronic bronchitis/Emphysema         | no = 0, yes = 1       | no = 0, yes = 1           |
| Sinusitis                            | no = 0, yes = 1       | no = 0, yes = 1           |
| Cancer                               | no = 0, yes = 1       | no = 0, yes = 1           |
| Stomach/Intestinal ulcer             | no = 0, yes = 1       | no = 0, yes = 1           |
| Urinary incontinence                 | no = 0, yes = 1       | no = 0, yes = 1           |
| Cataracts                            | no = 0, yes = 1       | no = 0, yes = 1           |
| Glaucoma                             | no = 0, yes = 1       | no = 0, yes = 1           |
| Hysterectomy/Oophorectomy            | no = 0, yes = 1       | no = 0, yes = 1           |
| Mental illness                       | no = 0, yes = 1       | no = 0, yes = 1           |
| Other long-term condition            | no = 0, yes = 1       | no = 0, yes = 1           |
| Need help with personal care         | no = 0, yes = 1       | no = 0, yes = 1           |
| Need help with personal affairs      | no = 0, yes = 1       | no = 0, yes = 1           |
| Confined to a bed or chair most of the day | no = 0, yes = 1   | no = 0, yes = 1           |
| Diabetes                             | no = 0, yes = 1       | no = 0, yes = 1           |
| PVD                                  | no = 0, yes = 1       | no = 0, yes = 1           |
| Stroke                               | no = 0, yes = 1       | no = 0, yes = 1           |
| Able to go outside in good weather   | yes without assistance = 0, yes with assistance = 0.5, no = 1 | yes = 0, no = 1           |
| Systolic blood pressure              | 90-140 = 0, <90 & > 160 = 1 | 90-140 = 0, <90 & > 140 = 1 |
| LDL                                  | <3.3 = 0, 3.3-4.1 = 0.333, 4.1-4.9 = 0.666, >4.9 = 1 | <3.3 = 0, ≥3.3 = 1         |
| Physical activity (3x weekly)        | yes, for more than 6 months = 0, yes, for less than 6 months = 0.25, no, but intend to in the next 30 days = 0.5, no, but I intend to in the next 6 months = 0.75, no, and I do not intend to = 1 | yes = 0, no = 1           |
| Variable name                           | Ordinal response/code | Dichotomous response/code |
|----------------------------------------|-----------------------|---------------------------|
| Hospitalization in past year           | no = 0, yes = 1       | no = 0, yes = 1           |
| Heart attack                           | no = 0, yes = 1       | no = 0, yes = 1           |
| Chronic lung disease                   | no = 0, yes = 1       | no = 0, yes = 1           |
| Osteoporosis                           | no = 0, yes = 1       | no = 0, yes = 1           |
| Parkinson disease                      | no = 0, yes = 1       | no = 0, yes = 1           |
| Stroke or CVD                          | no = 0, yes = 1       | no = 0, yes = 1           |
| Asthma                                 | no = 0, yes = 1       | no = 0, yes = 1           |
| Cancer                                 | no = 0, yes = 1       | no = 0, yes = 1           |
| Cataracts                              | no = 0, yes = 1       | no = 0, yes = 1           |
| High blood cholesterol                 | no = 0, yes = 1       | no = 0, yes = 1           |
| Long-term illness                      | no = 0, yes = 1       | no = 0, yes = 1           |
| High blood pressure                    | no = 0, yes = 1       | no = 0, yes = 1           |
| Diabetes or high blood sugar           | no = 0, yes = 1       | no = 0, yes = 1           |
| Arthritis                              | no = 0, yes = 1       | no = 0, yes = 1           |
| Stomach or duodenal ulcer              | no = 0, yes = 1       | no = 0, yes = 1           |
| Hip or femoral fracture                | no = 0, yes = 1       | no = 0, yes = 1           |
| Heart trouble or angina                | no = 0, yes = 1       | no = 0, yes = 1           |
| Falling down                           | no = 0, yes = 1       | no = 0, yes = 1           |
| Stomach or intestine problems          | no = 0, yes = 1       | no = 0, yes = 1           |
| Difficulty biting on hard foods        | no = 0, yes = 1       | no = 0, yes = 1           |
| Dizziness                              | no = 0, yes = 1       | no = 0, yes = 1           |
| Breathlessness                         | no = 0, yes = 1       | no = 0, yes = 1           |
| Incontinence                           | no = 0, yes = 1       | no = 0, yes = 1           |
| Swollen legs                           | no = 0, yes = 1       | no = 0, yes = 1           |
| Require dentures                       | no = 0, yes = 1       | no = 0, yes = 1           |
| Persistent cough                       | no = 0, yes = 1       | no = 0, yes = 1           |
| Pain in any joint                      | no = 0, yes = 1       | no = 0, yes = 1           |
| Climbing several flights of stairs     | no = 0, yes = 1       | no = 0, yes = 1           |
| Pulling/pushing large objects          | no = 0, yes = 1       | no = 0, yes = 1           |
| Dressing                               | no = 0, yes = 1       | no = 0, yes = 1           |
| Eating                                 | no = 0, yes = 1       | no = 0, yes = 1           |
| Using a map to get around              | no = 0, yes = 1       | no = 0, yes = 1           |
| Stooping/kneeling/crouching            | no = 0, yes = 1       | no = 0, yes = 1           |
| Managing money                         | no = 0, yes = 1       | no = 0, yes = 1           |
| Lifting/carrying weights >5 kg         | no = 0, yes = 1       | no = 0, yes = 1           |
| Getting in or out of bed               | no = 0, yes = 1       | no = 0, yes = 1           |
| Walking across a room                  | no = 0, yes = 1       | no = 0, yes = 1           |
| Making telephone calls                 | no = 0, yes = 1       | no = 0, yes = 1           |
| Sitting for about two hours            | no = 0, yes = 1       | no = 0, yes = 1           |
| Walking 100 meters                     | no = 0, yes = 1       | no = 0, yes = 1           |
| Getting up from a chair                | no = 0, yes = 1       | no = 0, yes = 1           |
| Preparing a hot meal                   | no = 0, yes = 1       | no = 0, yes = 1           |
| Taking medications                     | no = 0, yes = 1       | no = 0, yes = 1           |
| Variable                                | Coding                                                                 |
|----------------------------------------|------------------------------------------------------------------------|
| Bathing or showering                   | no = 0, yes = 1                                                        |
| Reaching or extending arms             | no = 0, yes = 1                                                        |
| Picking up a small coin from table     | no = 0, yes = 1                                                        |
| Using the toilet                       | no = 0, yes = 1                                                        |
| Shopping for groceries                 | no = 0, yes = 1                                                        |
| Doing work around house/garden         | no = 0, yes = 1                                                        |
| Appetite and eating                    | no = 0, yes = 1                                                        |
| Suicidality                            | no = 0, yes = 1                                                        |
| Lack of enjoyment                      | no = 0, yes = 1                                                        |
| Trouble sleeping                       | no = 0, yes = 1                                                        |
| Fatigue                                | no = 0, yes = 1                                                        |
| Fear of falling down                   | no = 0, yes = 1                                                        |
| Felt depressed                         | no = 0, yes = 1                                                        |
| Pessimism                              | no = 0, yes = 1                                                        |
| Interest                               | no = 0, yes = 1                                                        |
| Concentration                          | no = 0, yes = 1                                                        |
| Limitations with activities            | not limited = 0, limited but not severely = 0.5, severely limited = 1 |
| Frequency of vigorous activities       | more than once a week = 0, once a week = 0.33, one to three times a week = 0.67, hardly ever, or never = 1 |
| Frequency of moderate activities       | more than once a week = 0, once a week = 0.33, one to three times a week = 0.67, hardly ever, or never = 1 |
| Problems with eyesight                 | excellent = 0, very good = 0.25, good = 0.5, fair = 0.75, poor = 1    |
| Hearing problems                       | excellent = 0, very good = 0.25, good = 0.5, fair = 0.75, poor = 1    |
| Self-rated health                      | excellent = 0, very good = 0.25, good = 0.5, fair = 0.75, poor = 1    |
| Orientation                            | 4 correct responses = 0, 3 correct = 0.25, 2 correct = 0.5, 1 correct = 0.75, 0 correct = 1.0 |
| Mathematical performance               | 4 correct responses = 0, 3 correct = 0.25, 2 correct = 0.5, 1 correct = 0.75, 0 correct = 1.0 |
| Delayed recall test                    | 6 words or more recalled = 0, 5 words recalled = 0.25, 4 words = 0.5, 2 to 3 words = 0.25, 1 or 0 words = 1 |
| Verbal fluency score                   | 25 or more animals named = 0, 21 to 24 named = 0.25, 17 to 20 named = 0.5, 13 to 16 named = 0.75, 12 or fewer named = 1 |

The survey of health, ageing and retirement in Europe
The Survey of Health, Ageing and Retirement in Europe (SHARE) represents community-dwelling people aged 50 years and older across many European countries, and their spouses/partners [7]. Here, we included baseline data from the first two waves of SHARE (wave 1, 2004/2005: Austria, Belgium, Denmark, France, Germany, Greece, Israel, Italy, The Netherlands, Spain, Sweden, and Switzerland; wave 2, 2006/2007: Czech Republic, Poland, and Ireland) in which 37,546 individuals participated (mean age = 64.2, SD = 10.5 years; 56% female). We excluded spouses/partners under 50 years of age (n = 1,228). Mortality at 5 years was obtained from the second (2006/2007) and third waves (2008/2009) of SHARE for all countries except Israel and Ireland, where follow up data were not collected.

The Yale precipitating events project
The Yale Precipitating Events Project (Yale-PEP) is a cohort study based in greater New Haven, Connecticut. Individuals were 70 years and older at the study's inception (mean age = 78.4, SD = 5.3) [8,9]. The Yale-PEP survey contains longitudinal data of 754 community-dwelling, English-speaking, non-disabled persons who were not
| Variable name                          | Ordinal response/code | Dichotomous response/code |
|---------------------------------------|-----------------------|---------------------------|
| Help eating                           | no = 0, yes = 1       | no = 0, yes = 1           |
| Help grooming                         | no = 0, yes = 1       | no = 0, yes = 1           |
| Help using toilet                     | no = 0, yes = 1       | no = 0, yes = 1           |
| Help up/down stairs                   | no = 0, yes = 1       | no = 0, yes = 1           |
| Help lifting 10 lbs.                   | no = 0, yes = 1       | no = 0, yes = 1           |
| Help shopping                         | no = 0, yes = 1       | no = 0, yes = 1           |
| Help with housework                   | no = 0, yes = 1       | no = 0, yes = 1           |
| Help with meal preparations           | no = 0, yes = 1       | no = 0, yes = 1           |
| Help taking medication                | no = 0, yes = 1       | no = 0, yes = 1           |
| Help with finances                    | no = 0, yes = 1       | no = 0, yes = 1           |
| Lost more than 10 pounds in the last year | no = 0, yes = 1   | no = 0, yes = 1           |
| High blood pressure                   | no = 0, yes = 1       | no = 0, yes = 1           |
| How health has changed in last year   | better = 0, same = 0.5, worse = 1 | better/same = 0, worse = 1 |
| Heart attack                          | no = 0, suspected = 0.5, yes = 1 | no = 0, yes/suspected = 1 |
| CHF                                   | no = 0, suspected = 0.5, yes = 1 | no = 0, yes/suspected = 1 |
| Stroke                                | no = 0, suspected = 0.5, yes = 1 | no = 0, yes/suspected = 1 |
| Cancer                                | no = 0, suspected = 0.5, yes = 1 | no = 0, yes/suspected = 1 |
| Diabetes                              | no = 0, suspected = 0.5, yes = 1 | no = 0, yes/suspected = 1 |
| Arthritis                             | no = 0, suspected = 0.5, yes = 1 | no = 0, yes/suspected = 1 |
| Chronic lung disease                  | no = 0, suspected = 0.5, yes = 1 | no = 0, yes/suspected = 1 |
| Feel everything is an effort          | rarely = 0, sometimes = 0.5, most of the time = 1 | rarely = 0, most/some of the time = 1 |
| Feel depressed                        | rarely = 0, sometimes = 0.5, most of the time = 1 | rarely = 0, most/some of the time = 1 |
| Feel happy                            | most of the time = 0, sometimes = 0.5, rarely = 1 | most/some of the time = 0, rarely = 1 |
| Feel lonely                           | rarely = 0, sometimes = 0.5, most of the time = 1 | rarely = 0, most/some of the time = 1 |
| Have trouble getting going           | rarely = 0, sometimes = 0.5, most of the time = 1 | rarely = 0, most/some of the time = 1 |
| BMI                                   | 18.5-24.99 = 0, <18.5 & 25-30 = 0.5, >30 = 1 | 18.5-24.99 = 0, <18.5 & > 25 = 1 |
| Walk outside                          | often = 0, sometimes = 0.333, seldom = 0.666, never = 1 | often = 0, sometimes/seldom/never = 1 |
| Self-rating of health                 | excellent = 0, very good = 0.25, good = 0.5, fair = 0.75, poor = 1 | good/very good/excellent = 0, fair/poor = 1 |
| MMSE                                  | >25 = 0, 21-24 = 0.25, 18-20 = 0.5, 10-17 = 0.75, <10 = 1 | >24 = 0, <24 = 1 |
| Usual pace                            | <9.3 = 0, 9.3-10.7 = 0.25, 10.8-12.6 = 0.5, 12.7-15.5 = 0.75, >15.5 = 1 | ≤16 = 0, >16 = 1 |
| Rapid pace                            | <7.0 = 0, 7.0-8.4 = 0.25, 8.5-10.4 = 0.5, 10.5-12.9 = 0.75, >12.9 = 1 | ≤10 = 0, >10 = 1 |
| Peak flow                             | Men                    | Men                       |
|                                       | >526 = 0, 461-525 = 0.25, 408-460 = 0.5, 311-407 = 0.75, <310 = 1 | >340 = 0, ≤340 = 1 |
|                                       | Women                  | Women                     |
|                                       | >366 = 0, 324-366 = 0.25, 264-323 = 0.5, 210-263 = 0.75, <210 = 1 | >310 = 0, ≤310 = 1 |
| Shoulder strength                     | Men                    | Men                       |
|                                       | >16.37 = 0, 14.57-16.36 = 0.25, 13.26-14.56 = 0.5, 10.83-13.25 = 0.75, <10.82 = 1 | >12 = 0, ≤12 = 1 |
|                                       | Women                  | Women                     |
|                                       | >13.00 = 1, 11.10-12.90 = 0.25, 9.40-11.00 = 0.5, 7.30-9.30 = 0.75, <7.29 = 1 | >9 = 0, ≤9 = 1 |
terminally ill. At baseline, most participants were women (n = 487, 64.6%), and the majority were white (n = 682, 90.5%), with a mean Mini-Mental State Examination (MMSE) [10] score of 26.8 (SD = 2.50). Death data were obtained from a follow up survey 155 months after baseline. Mortality is ascertained monthly and all deaths have been confirmed via death certificates [11].

Frailty index

For each dataset, we constructed two frailty indices from baseline data following a standard procedure [5]. Within each dataset, one frailty index (FI_dichotomous) was constructed from only dichotomous health variables (indicating the absence or presence of a deficit) and in the other frailty index (FI_ordinal), as many variables as possible were ordinally coded (indicating the severity of a deficit, e.g. 0, 0.5, 1); both frailty indices in each dataset included the same variables and were constructed by the same member of our team. Across datasets, the frailty indices varied in the number of variables included, the proportion of variables that were only available as dichotomous measures, and in duration of follow-up. The FI_ordinal for NSHS included nineteen 2-level variables, two 3-level, one 4-level, and one 5-level variable (Total 23 variables, Table 1). The FI_ordinal for SHARE included sixty 2-level variables, one 3-level variable, two 4-level, and seven 5-level variables (Total 70 variables, Table 2). The FI_ordinal for Yale-PEP included twelve 2-level variables, fourteen 3-level variables, one 4-level, and six 5-level variables (Total 33 variables, Table 3). Scores on all frailty indices were calculated by dividing the sum of values on all included variables (deficits) out of the total number of non-missing variables. Participants missing >20% of data for variables in a frailty index were excluded for analysis of that frailty index [12].

Statistical analysis

For each frailty index, we calculated mean scores (adjusted for sex) and tested the statistical significance of differences between the FI_ordinal and FI_dichotomous within each dataset using analyses of variance (ANOVA). To assess the impact of any differences between the FI_dichotomous and FI_ordinal for each dataset, we verified proportionality and performed multivariable Cox regression analyses for survival. The hazard ratios (HR) and 95% confidence intervals (CIs) for the two indices were adjusted for age and sex. Finally, we evaluated the difference in the ability of both FIs to predict mortality using Receiver Operating Characteristic (ROC) curves and compared the areas under the ROC curve. The statistical significance level was set to 0.05 and all calculations were performed using PASW18. Approval for the secondary analyses presented here came from the Research Ethics Committee of the Capital District Health Authority, Halifax, Nova Scotia, Canada.

Results

In SHARE and Yale-PEP, mean frailty index scores were significantly greater (p < 0.001) for the FI_ordinal compared with the FI_dichotomous whereas in NSHS the FI_dichotomous was greater (p < 0.001) (Table 4). The differences in mean scores between the two frailty indices from the same dataset were less than 0.02 in all datasets, which represents less than 1 deficit for NSHS and Yale-PEP and about 1.5 deficits for SHARE. The confidence intervals obtained from the Cox regression hazard ratios for FI_ordinal and FI_dichotomous overlapped (Table 5); absolute differences between the hazard ratios for the two FIs was 0.001 for SHARE, 0.008 for NSHS, and 0.009 for Yale-PEP. In each model, the age and sex covariates were also significant (p-value < 0.05). In Yale-PEP, 72.7% of the participants had died by 13 years follow-up, in NSHS 12.1% were deceased after 10 years, and in SHARE 11.7% had died by 5 years. The areas under the ROC curves for mortality prediction were the same for the FI_ordinal and FI_dichotomous in each dataset (Figure 1); their absolute differences ranged from 0 (SHARE, NSHS) to 0.02 (Yale-PEP) (Table 4). This pattern did not change when analyses were stratified by sex.

Discussion

In this secondary analysis of data from the NSHS, SHARE, and Yale-PEP studies, we constructed two

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Table 4 Mean values and predictive ability of the frailty indices constructed with and without dichotomization of health deficits included in each frailty index

| Survey   | Male FI_ordinal (SD) | Male FI_dichotomous (SD) | Male FI_ordinal (SD) | Male FI_dichotomous (SD) | Female FI_ordinal (SD) | Female FI_dichotomous (SD) | ROC area (CI) | Female FI_ordinal (SD) | Female FI_dichotomous (SD) |
|----------|----------------------|--------------------------|----------------------|--------------------------|------------------------|--------------------------|--------------------------|------------------------|--------------------------|
| NSHS     | 0.10 (0.08)          | 0.11 (0.08)             | 0.12 (0.10)          | 0.13 (0.11)             | 0.76 (0.73,0.80)       | 0.76 (0.73,0.79)        | 0.80 (0.77,0.84)       | 0.80 (0.77,0.83)       |
| SHARE    | 0.16 (0.12)          | 0.13 (0.12)             | 0.19 (0.13)          | 0.17 (0.14)             | 0.77 (0.75,0.78)       | 0.77 (0.75,0.78)        | 0.78 (0.76,0.80)       | 0.78 (0.76,0.80)       |
| Yale-PEP | 0.23 (0.10)          | 0.21 (0.12)             | 0.26 (0.11)          | 0.25 (0.14)             | 0.70 (0.63,0.77)       | 0.69 (0.62,0.76)        | 0.68 (0.63,0.73)       | 0.66 (0.61,0.71)       |

*Significant differences between ordinal and dichotomous FIs for both males and females (p < 0.05).
SD = Standard Deviation, CI = Confidence Intervals, FI = frailty index.
SHARE = Survey of Health, Ageing and Retirement in Europe.
NSHS = Nova Scotia Health Survey.
Yale-PEP = Yale Precipitating Events Project.
frailty indices for each dataset using the same variables but coding them differently; one included both dichotomous and ordinal variables (FI_{ordinal}) whereas the other included only dichotomous variables (FI_{dichotomous}). After comparing the ordinal and dichotomous frailty indices within each dataset, we found that their mean values and their ability to predict mortality were nearly identical. These findings, based on three diverse datasets, quantitatively confirm the flexible nature of the frailty index approach in relation to deficit variable coding. Our findings must be interpreted with caution. The samples from all three studies only included community-dwelling individuals. Our findings may not be generalizable to other populations such as institutionalized older adults and hospitalized patients. Even so, to maximize the generalizability of our results we included three diverse samples from different studies. The SHARE included Europeans age 50 and older with a follow up period of 5 years and Yale-PEP included Americans age 70 and older with a follow up period of 12 years. Note that the NSHS included Canadians age 18 and older with a follow up period of 10 years. In prior work we have calculated a frailty index for persons across the lifespan, starting at age 15 years [13]. It appears that the frailty index serves as a proxy measure of ageing [2,14,15]. This view (of the frailty index reflecting the deficit accumulation that drives mortality) has also been developed by other groups [16-18]. Other lines of evidence point to the importance of deficit accumulation prior to age 50 as a determinant of what happens in later life. For example, genes associated with greater longevity are typically associated with less deficit accumulation at younger ages [19] whereas states such as intellectual disability typically are associated with higher levels of deficit accumulation at younger ages (which nevertheless increase across the life course) [20]. Hence, there is a need to understand the impact that different scoring systems might have across the lifespan. Further, we chose to compare the predictive validity of the frailty indices using all-cause mortality at different lengths of follow-up. While the frailty index is not meant simply to predict mortality, all-cause mortality is useful here as it is dichotomous, easily verifiable and non-arbitrary.

In SHARE and Yale-PEP, the mean frailty index score was slightly higher for the FI_{ordinal} compared with the FI_{dichotomous}, whereas in the NSHS the opposite was true. Even so, in all datasets the difference was minor, representing less than 1-1.5 items in the index. This is somewhat expected behavior for a frailty index. The criteria

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**Table 5** Cox proportional hazard ratios (HR) and 95% confidence intervals for time until death

| Survey                  | NSHS     | SHARE     | Yale-PEP |
|-------------------------|----------|-----------|----------|
| FI-type                 | F_{ordinal} | F_{dichotomous} | F_{ordinal} | F_{dichotomous} | F_{ordinal} | F_{dichotomous} |
| HR Fl (CI)              | 1.04 (1.03,1.05) | 1.03 (1.02,1.04) | 1.04 (1.04,1.04) | 1.04 (1.04,1.04) | 1.04 (1.03,1.05) | 1.03 (1.02,1.04) |
| HR age (CI)             | 1.11 (1.10,1.12) | 1.11 (1.10,1.12) | 1.08 (1.07,1.09) | 1.08 (1.08,1.09) | 1.08 (1.06,1.09) | 1.08 (1.06,1.10) |
| HR sex (CI)             | 0.51 (0.41,0.62) | 0.53 (0.42,0.65) | 0.50 (0.45,0.55) | 0.50 (0.45,0.55) | 0.65 (0.54,0.79) | 0.64 (0.53,0.77) |
| p-value Fl              | <10^{-6} | <10^{-6} | <10^{-43} | <10^{-43} | <10^{-5} | <10^{-5} |
| p-value age             | <10^{-6} | <10^{-6} | <10^{-43} | <10^{-43} | <10^{-5} | <10^{-5} |
| p-value sex             | <10^{-6} | <10^{-6} | <10^{-43} | <10^{-43} | <10^{-5} | <10^{-5} |

CI = Confidence Intervals, FI = frailty index.
SHARE = Survey of Health, Ageing and Retirement in Europe.
NSHS = Nova Scotia Health Survey.
Yale-PEP = Yale Precipitating Events Project.

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**Figure 1** The ability of the frailty index to predict mortality (ROC curves). The ordinal (solid line) and dichotomous (segmented lines) frailty indices (FIs) are compared. Thick lines indicate males and thin lines females.
used to create a dichotomous variable from an ordinal one rely on the researcher (in this case, members of our research group), and it is expected that there may be differences between cutoff points among different researchers. However, this difference is expected to be minimal when at least 30 variables are included, and is expected not to be consistently higher or lower.

The mean frailty index scores differed across datasets, being highest in the oldest dataset (Yale-PEP) and lowest in the youngest (NSHS). Similarly, the mean score of the frailty indices and their predictive ability were different across datasets, but not between the two paired frailty indices within a dataset, which was the intended comparison. Across datasets, the risk associated with each increment in the frailty index crucially depends on the ambient or background level of risk, and so will differ. For this ambient risk, the outcomes of people with the lowest cores (e.g. frailty index = 0) can serve as an estimate [21].

Conclusions
The frailty index provides a useful way to quantify the accumulation of relatively small health deficits across multiple physiological systems, and to identify and grade a state of overall vulnerability to outcomes. Based on our analysis of three diverse datasets we found that, if enough variables are included, dichotomizing variables or using them in an ordinal form appears to have little impact on three important properties of the frailty index: the mean score, gender differences, and the ability to predict mortality.

Abbreviations
Fi: Frailty index; NSHS: Nova Scotia Health Survey; SHARE: Survey of Health, Ageing and Retirement in Europe; Yale-PEP: Yale Precipitating Events Project; ROC: Receiver operating characteristic; ANOVA: Analysis of variance; HR: Cox hazard ratio; CI: Confidence interval; SD: Standard Deviation; MMSE: Mini-Mental State Examination.

Competing interests
KR and AM are applying for funding to commercialize a version of the Frailty Index based on a Comprehensive Geriatric Assessment. A company called Videx Canada has been incorporated for this. The version of the frailty index presented here is not the one that Videx aims to commercialize.

Authors’ contributions
FP, OT, LW, TB conceived the article, conducted the analyses, and wrote the final draft. AM arranged for the Yale-PEP data to be made available to our group and assisted with data analysis. KR contributed to the conception and initial design of the study, arranged funding, and revised previous drafts. TG and EG arranged for the Yale-PEP data to be made available to our group and revised previous drafts. SK arranged for the NSHS data to be made available to our group and revised previous drafts. All authors read and approved the final manuscript.

Acknowledgements
Funding Sources: KR receives funding from the Dalhousie Medical Research Foundation as the Kathryn Allen Weldon Professor of Alzheimer Research. KR and AM are supported by operating grants from the Canadian Institutes of Health Research. OT is supported by a Banting Fellowship.

We thank Karina Davidson and Daichi Shimbo, investigators for the Nova Scotia Health Survey, for making the data available to us. This paper uses data from SHARE wave 4 release 1.1.1, as of March 28th 2013 or SHARE wave 1 and 2 release 2.5.0, as of May 24th 2011 or SHARELIFE release 1, as of November 24th 2010. The SHARE data collection has been primarily funded by the European Commission through the 5th Framework Programme (projects QLK6-CT-2001-00360 in the thematic programme Quality of Life), through the 6th Framework Programme (projects SHARE-I3, RI-CT-2006-062193, COMPARE, CIT5- CT-2005-028857, and SHARELIFE, CIT4- CT-2006-028812) and through the 7th Framework Programme (SHARE-PREP, No° 211909, SHARE-LEAP, No° 227822 and SHARE-MA, No° 261982). Additional funding came from the U.S. National Institute on Aging (1U01 AG09740-1352, P01 AG05842, P01 AG08219, P30 AG12815, R21 AG025162, Y1-AG-4553-01, JAG BSRIK-11 and OGHA 04-064) and the German Ministry of Education and Research as well as from various national sources is gratefully acknowledged (see www.share-project.org for a full list of funding institutions).

R37AG15760 (which funds PEI) and Dr. Gill is supported, in part, by K07AG043587 and P30AG021342.

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Received: 9 July 2013 Accepted: 18 February 2014
Published: 24 February 2014

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doi:10.1186/1471-2318-14-25
Cite this article as: Peña et al.: Comparison of alternate scoring of variables on the performance of the frailty index. BMC Geriatrics 2014 14:25.