*Age and Ageing* 1996;25:386–391

# Evidence for a Non-linear Relationship between Leg Strength and Gait Speed

DAVID M. BUCHNER, ERIC B. LARSON, EDWARD H. WAGNER, THOMAS D. KOEPSELL, BARBARA J. DE LATEUR.

*Summary*

Although the relationship between strength and physical performance in older adults is probably non-linear, few empirical studies have demonstrated that this is so.

In a population-based sample of adults aged 60–96 years (n = 409), leg strength was measured in four muscle groups (knee extensor, knee flexor, ankle plantar flexor, ankle dorsiflexor) of both legs using an isokinetic dynamometer. A leg strength score was calculated as the sum of the four strength measurements in the right leg. Usual gait speed was measured over a 15.2 metre course.

With a linear model, leg strength explained 17% of the variance in gait speed. Non-linear models (quadratic and inverse) explained significantly more variance (22%). The nature of the non-linear relationship was that, in stronger subjects, there was no association between strength and gait speed, while in weaker subjects, there was an association. Body weight and age also explained significant amounts of variance in gait speed, while sex and height did not.

The results supported the hypothesis of a non-linear relationship between leg strength and gait speed that is similar for older men and women. This finding represents a mechanism for how small changes in physiological capacity may have substantial effects on performance in frail adults, while large changes in capacity have little or no effect in healthy adults.



## Introduction

Older adults show age-related decline in physical performance. A growing body of research seeks to identify the determinants of performance, and so elucidate the reasons for decline. Because of the obvious relationship between physical fitness and physical performance, skeletal muscle strength is a commonly studied determinant.

We [1, 2] and others [3] have hypothesized a non-linear relationship between strength and performance. Specifically, we mean a curve that is partly straight and partly curved (some use the term 'curvilinear' to describe such a curve). Figure 1 illustrates the hypothesis for the instance of leg strength and usual gait speed. (Herein, we regard 'gait speed' and 'walking' speed as synonyms, and regard 'comfortable', 'usual', 'normal', and 'preferred gait' speed as synonyms.) Area A (the straight part) corresponds to the range where strength is sufficient for normal walking, and where changes in strength do not affect gait speed. Area B (the curved part) corresponds to the range of marginal or inadequate strength. Here, changes in strength cause changes in gait speed. In Area C, strength is below the minimum needed to walk.

However, the statistical methods of published studies typically assume a linear relationship between strength and performance. For example, a recent review of eight studies found that all employed a correlation coefficient [4]. If Figure 1 is correct, the size of the correlation will vary according to case mix of the study sample. Interestingly, reported correlations for the relationship of strength and gait speed have varied. Two studies in community adults reported a non-significant correlation between strength and gait speed [5, 6], and another found that three groups that differed in gait speed did not differ in knee strength [7]. Other studies have reported significant, moderate correlations (R = 0.36–0.42) [8, 9] and some have reported high correlations between either leg strength [10] or leg power [11].

The purpose of this study was to test for a non-linear relationship between strength and gait speed. The study also assessed whether a threshold can be identified at which age-related loss in strength begins to affect gait speed, and the usefulness of measures of relative strength.

### Methods

*Study sample:* The sample was an age- and sex-stratified random sample of adults enrolled in a large Health Maintenance Organization (Group Health Cooperative) in

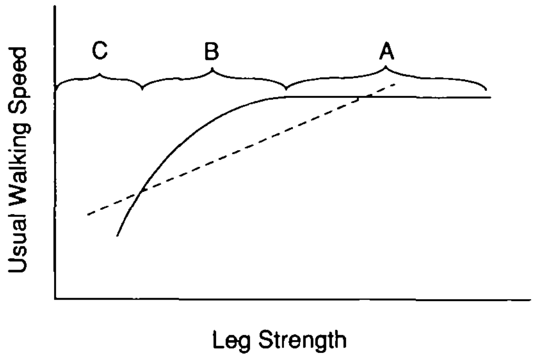


*Figure 1*. Hypothesized relationship between leg strength and usual gait speed. Area A corresponds to the range where strength is sufficient for normal walking, and where changes in strength affect physiological reserve but not gait speed. Area B corresponds to the range of marginal or inadequate strength. In Area B, changes in strength cause changes in gait speed, and there exists a curve that quantifies the relationship. In Area C, strength is below the minimum need to walk at all.

western Washington State, USA. Adults were excluded if they had: (1) neurological conditions affecting skeletal muscle (e.g. stroke, polio, dementia); (2) musculoskeletal diseases affecting muscle (e.g. polymyalgia rheumatica, rheumatoid arthritis); (3) systemic illness with effects on muscle (e.g. hyperthyroidism, chronic cortiscosteroid use); (4) inability to walk or terminal illness. Adults with non-muscular pathologies influencing walking (e.g. knee arthritis) were not excluded, as a purpose of the study was to estimate the effect of muscular weakness on performance in older adults who should have a normal response to strengthening exercise. Of 1362 adults sampled, 29% were excluded, 39% refused participation, and 32% (434) participated (estimated participation rate of eligible subjects in the population = 61%). Factors affecting participation by older adults in research studies at Group Health have been examined. Though participation is associated with lower income, less education, and lower involvement in community organizations, participation is not associated with health status [12], suggesting the health status mix of this study may be reasonably representative. Owing to missing data, the number of subjects in the analysis was 409. The characteristics of the study sample are shown in Table I.

*Study measures:* Leg strength was measured with a Cybex II+ isokinetic dynamometer using standard Cybex protocols. Four muscle groups were measured: knee extensor, knee flexor, ankle plantar flexor, and ankle dorsiflexor. Strength was measured in both legs, with a knee-joint rotation speed of 60°/s, and an ankle-joint rotation speed of 30°/s. Subjects were familiarized with the protocol before testing. Tests were done in random order to exclude learning effects. The reliability of the leg strength measurements was excellent (e.g. same day test–retest correlation was Pearson $R = 0.95$ for knee extensor strength). Later studies of the reliability of ankle strength measures showed them to be equally reliable [13].

Usual gait speed was measured over a 15.2 m (50 ft) course. Subjects began the test from a standing position, and were instructed to walk at their usual pace. Same day test–retest reliability was Pearson $R = 0.94$.

*Statistical analysis:* Multiple regression analysis was used to test for non-linear relationships. In all analyses reported, residual analysis confirmed fit of the regression models, though two outliers were excluded from all regression analyses to obtain acceptable fit. When the outliers were included in the analysis, the results were essentially the same, except the regression models explained 1–2% more of the variance, and non-linear effects were slightly greater.

As the primary test for a non-linear relationship between strength and gait speed, regression analysis tested whether strength squared (quadratic transformation) explained more variance than strength alone. A second test of the non-linear relationship sought to show that a strength cut point could be identified whereby, for subjects with strength above the cut point, the slope equalled zero for the regression line between strength and gait speed.

To develop a quantitative model between leg strength and gait speed, we hypothesized an inverse transformation of strength could provide a reasonable first approximation to the hypothetical curve in Figure 1. The inverse model could produce a curve that is only slightly curved at one end approximating the straight line in Area A of Figure 1, and more curved at the other end approximating the curve in Area B of Figure 1.

The leg strength measures were highly correlated. Principal components analysis showed that a single factor explained 78% of the variance in strength measurements. Regression

*Table I*. Subject characteristics (n = 409)

| | Mean (SD) or percentage |
|---|---|
| Age (years): | |
| 60–69 | 25% |
| 70–79 | 42% |
| 80–96 | 33% |
| Female | 60% |
| Caucasian | 97% |
| Education: | |
| < 12 years | 25% |
| 12 years | 23% |
| > 12 years | 52% |
| Retired | 83% |
| Currently married | 54% |
| Right handed | 95% |
| Excellent or good health | 92% |
| Sickness impact profile physical dimension | 3.5 (5.9) |
| Weight (kg) | 71 (14) |
| Height (m) | 1.64 (0.10) |
| Usual gait speed (m/min) | 73 (16) |
| Right grip strength (kg) | 10 (5) |
| Right knee extensor (Nm) | 87 (35) |
| Right knee flexor (Nm) | 45 (23) |
| Right plantar flexor (Nm) | 40 (22) |
| Right dorsi-flexor (Nm) | 15 (7) |
| Leg strength score (Nm) | 189 (81) |
| Leg strength score/weight (Nm/kg) | 2.65 (0.91) |

Note: Knee strength measured at 60°/s; ankle strength measured at 30°/s; leg strength score calculated by adding absolute knee extensor, knee flexor, ankle plantar flexor, and ankle dorsiflexor strengths of the right leg.

analyses were simplified by using a single strength variable which summarized all the leg strength measures. Five potential scores were considered: (1) a sum of the four Z scores for the strength measures in the right leg; (2) a sum of the eight Z scores of the strength measures of both legs; (3) a strength factor score, calculated using principal components analysis and based upon all eight measurements; (4) a sum of the absolute strength of muscle groups in the right leg; and (5) a sum of the absolute strength of muscle groups in both legs. Our choice is explained below.

## Results

*Relationship among leg strength measurements:* The eight leg strength measurements were highly correlated (Table II). The correlations between the left and right legs in the same muscle group were high (R = 0.80–0.89), and slightly higher than correlations among different muscle groups of the same leg (R = 0.67–0.87).

The five summary measures of absolute leg strength proved almost identical. The correlation among summary scores was R = 0.97–0.99. We chose one score, sum of absolute strength in the right leg, for subsequent analysis. We refer to it as the leg strength score. We chose this score mainly for ease of computation by others seeking to replicate our results. The high correlations between the left and right legs in the same muscle group supported basing the score on measurements from a single leg. Since it is plausible that large muscle groups are more important to performance than small muscle groups, we found it acceptable that the score depended more upon large muscle groups. Table III shows correlations among the leg strength score and other variables used in the regression models.

For a measure of relative strength, we chose to divide the leg strength summary score by weight. We considered a relative strength measure that divided absolute strength by both height and weight, but the correlation between strength/weight and strength/weight/height was extremely high (R = 0.98). Also, the regression analyses discussed below showed height was not an independent predictor of gait speed after controlling for strength and weight.

*Relationship between gait speed and strength:* The first regression of Table IV provided evidence of a non-linear relationship between gait speed and strength. Strength, in a linear model, explained 17% of the variance in gait speed. The addition of a quadratic term to the model significantly improved the amount of variance explained to 22%. The second regression in Table IV shows that after adjustment for age, sex, height, and weight, both the linear and quadratic terms were still significant predictors of gait speed.

The inverse model (Table IV) provided additional evidence for a non-linear relationship between strength and gait speed. Stepwise, forward, and backward regression methods resulted in the same terms entering the model: weight, age, and the inverse transformation of strength were significant terms, while height, sex, and interaction terms were not. The model explained 37% of the variance in gait speed. An inverse model using relative strength explained the same amount of variance.

Line A in Figure 2 is the curve relating strength to gait speed from the inverse model. The curve is similar to that in Figure 1, though the slope of the curve in the higher ranges of strength is not zero as hypothesized. The analysis in Table V addressed whether a threshold in the leg strength score could be identified, where above the threshold the slope equalled zero for the regression line between strength and gait speed. At a cut point of 275 Nm, the slope was quite close to zero. For thresholds below 275 Nm, the lower the threshold, the more the slope differed from zero. Line B in Figure 2 modifies the inverse model so that above 275 Nm a zero slope occurs. Figure 3 provides a representation of the non-linear relationship that takes into account body weight.

*Table II.* Pearson correlation coefficients between isokinetic strength (Nm) of leg muscle groups in older adults (n = 409)

| | Right leg | | | | Left leg | | | |
|---|---|---|---|---|---|---|---|---|
| | Knee extensor | Knee flexor | Plantar flexor | Dorsi-flexor | Knee extensor | Knee flexor | Plantar flexor | Dorsi-flexor |
| ***Right leg*** | | | | | | | | |
| Knee extensor | – | | | | | | | |
| Knee flexor | 0.87 | – | | | | | | |
| Plantar flexor | 0.72 | 0.78 | – | | | | | |
| Dorsiflexor | 0.69 | 0.67 | 0.69 | – | | | | |
| ***Left leg*** | | | | | | | | |
| Knee extensor | **0.86** | 0.82 | 0.75 | 0.71 | – | | | |
| Knee flexor | 0.80 | **0.89** | 0.79 | 0.65 | 0.85 | – | | |
| Plantar flexor | 0.72 | 0.76 | **0.88** | 0.67 | 0.79 | 0.77 | – | |
| Dorsiflexor | 0.66 | 0.66 | 0.64 | **0.80** | 0.72 | 0.68 | 0.67 | – |

*Note:* Knee strength measured at 60°/s, and ankle strength at 30°/s. All correlation coefficients significant at the $p < 0.001$ level. Correlations between legs of the same muscle group are shown in bold.

*Table III.* Pearson correlation coefficients between leg strength summary score, body weight, height, age, sex, and gait speed (n = 409)

| | Strength summary score | Weight | Height | Age | Sex |
|---|---|---|---|---|---|
| Strength score | – | | | | |
| Weight | 0.55 | – | | | |
| Height | 0.64 | 0.62 | – | | |
| Age | −0.43 | −0.28 | −0.23 | – | |
| Sex | 0.64 | 0.47 | 0.71 | −0.02 | – |
| Gait speed | 0.42 | 0.09 | 0.21 | −0.49 | 0.10 |

*Note:* Sex was coded 0 = female, 1 = male; correlation coefficients of 0.10 and above are significant at the $p < 0.05$ level.

## Discussion

Usual gait speed declines with age. Other than slowness, there may be no age-specific alterations in gait. Young adults, when asked to walk slowly, adopt a gait pattern remarkably similar to that of older adults [14]. By reporting linear associations between gait speed with leg strength or power, several studies suggest age-related loss of strength partly explains decline in gait speed [8–11]. The present study results also provide evidence that age-related loss of strength is one factor causing decline in gait speed. However, the results support the hypothesis of a non-linear relationship between leg strength and usual gait speed.

The non-linear relationship represents a mechanism by which small changes in physiological capacity may produce relatively large effects on performance in frail adults, while large changes in capacity have little or no effect on daily function in healthy adults. It also can explain the disparate results of recent studies of resistance training. In frail adults, resistance training increased strength and also increased gait speed [15]. In stronger community adults, resistance training further increased strength, but did not affect gait speed [16].

The results did not suggest that models based upon relative strength were more useful than models based upon absolute strength. Pending further research, avoiding the use of relative strength terms seems wise. As a ratio term, relative strength can induce spurious correlations in regression equations [17].

We have suggested it might be possible to identify a threshold at which strength loss begins to affect performance [1]. While a leg strength score of around 275 Nm seemed near this hypothetical threshold, the more important finding was the gradual transition

*Table IV.* Non-linear models of usual gait speed in older adults: to allow comparison of the variance explained by terms across models, the column $R^2$ shows the cumulative variance explained by the model if terms are entered one step at a time (n = 407)

| Variable | Unstandardized regression coefficient (SE) Full model | p value Full model | Total $R^2$ at each step % |
|---|---|---|---|
| *Unadjusted quadratic model* | | | |
| Constant | 41.3 (4.0) | < 0.0001 | – |
| Strength (linear) | 0.258 (0.039) | < 0.0001 | 17 |
| Strength (quadratic) | −0.000399 (0.000087) | < 0.0001 | 22 |
| *Adjusted quadratic model* | | | |
| Constant | na | < 0.0001 | – |
| Age, sex, height, weight | na | < 0.0001 | 28 |
| Strength (linear) | 0.238 (0.039) | < 0.0001 | 34 |
| Strength (quadratic) | −0.000344 (0.000079) | < 0.0001 | 37 |
| *Inverse model* | | | |
| Constant | 163 (8.0) | < 0.0001 | – |
| Strength (inverse) | −2277 (266) | < 0.0001 | 22 |
| Weight | −0.257 (0.051) | < 0.0001 | 26 |
| Age | −0.759 (0.090) | < 0.0001 | 37 |
| *Inverse model (with relative strength)* | | | |
| Constant | 144.8 (6.2) | < 0.0001 | – |
| Strength/weight (inverse) | −33.8 (3.9) | < 0.0001 | 25 |
| Age | −0.748 (0.086) | < 0.0001 | 37 |

*Note:* Regression coefficients and significance levels are from full models, i.e. are adjusted for other terms in the model. Two outliers were removed from the inverse models (resulting in n = 407), and for consistency, these outliers are also removed from the quadratic models. In the two quadratic models, variables were entered in the order appropriate for testing hypotheses (see text). For the inverse models, variables eligible to enter were: age (years), sex (0 = female, 1 = male), weight (kg), height (m), and the inverse of either absolute or relative strength. Stepwise, backwards, and forwards regression resulted in the same significant terms in the inverse models. Sex, height, and interaction terms were not significant in any models.

*Table V*. Slopes of linear regression lines between usual gait speed and leg strength score: if the hypothesis illustrated in Figure 1 is correct, it should be possible to identify a threshold of strength, where above the threshold, the slope equals 0 for the linear regression line between gait speed and strength. This cut point divides Area A from Area B in Figure 1: the tabulated data report the slope of the regression line if only subjects with strength above various possible thresholds are included in the analysis

| | | Linear regression line between usual gait speed and leg strength | | |
|---|---|---|---|---|
| Threshold of leg strength score (Nm) | No. | Slope (adjusted for age and weight) | Standard error of slope | p value |
| All Subjects | 407 | 0.073 | 0.010 | 0.0001 |
| > 100 | 363 | 0.060 | 0.011 | 0.0001 |
| > 125 | 319 | 0.052 | 0.012 | 0.0001 |
| > 150 | 262 | 0.045 | 0.013 | 0.0009 |
| > 175 | 199 | 0.040 | 0.016 | 0.01 |
| > 200 | 148 | 0.039 | 0.020 | 0.06 |
| > 225 | 117 | 0.042 | 0.025 | 0.09 |
| > 250 | 91 | 0.022 | 0.032 | 0.5 |
| > 275 | 68 | 0.008 | 0.038 | 0.8 |

between the flat and very curved parts of curve B in Figure 2. There is no point that cleanly divides the two parts, and this difficulty in finding a threshold is similar to the results of another study [18]. A universal threshold may not exist if impairments in one determinant can be compensated for by physiological reserve in other determinants. If so, the threshold at which muscular weakness begins to affect performance will vary from person to person, depending upon physiological reserve in other determinants.

The results of this study should be interpreted in light of study limitations. While the study enrolled a population-based sample, about 40% of subjects refused to participate. There were few extremely strong or extremely weak subjects, so the relationship of strength to performance is not as accurately estimated at the extremes. The study is cross-sectional, and does not demonstrate that declines in strength over time are associated with the predicted decline in gait speed. If determinants of gait speed interact, the reported regression models over-simplify the relationship of gait speed to strength. We did not address whether measures of muscular endurance or power are more closely related to gait speed than muscle peak torque.

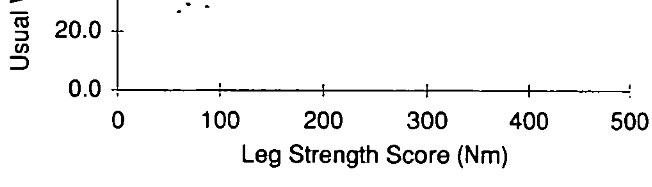


*Figure 2*. Plot of leg strength score versus usual gait speed with regression curves. Curve A is a plot of the inverse model (see Table IV) for the average age (76 years) and body weight (71 kg) of the study sample. Curve B modifies the inverse model according to the results shown in Table V—that above a strength score of 275 Nm or so, the slope should equal zero.

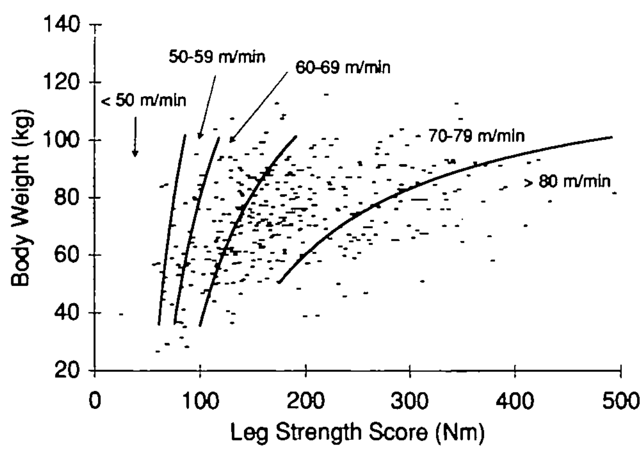


*Figure 3*. Predicted gait speed by leg strength score and body weight. A plot of strength versus weight is divided into areas according to the predicted gait speed for that area. Predicted gait speed is based upon the inverse model of Table IV (for a 76-year old adult). For example, a subject with strength score = 225 Nm and weight = 80 kg has a predicted gait speed of 70–79 m/min. The non-linear relationship between strength and gait speed is illustrated by the fact the dividing lines are much closer together at low leg strength scores than at high scores.

In conclusion, the results supported the hypothesis of a non-linear relationship between leg strength and gait speed, that is similar for older men and women. The results provide a mechanism for how small changes in physiological capacity produce large effects on performance in frail adults, while large changes in capacity have little or no effect on daily function in healthy adults. A point at which age-related strength loss begins to impair gait speed was not easily identified, perhaps partly because the point depends upon determinants of performance besides strength that vary from person to person.

*Acknowledgement*

The study was supported in part by grants from the National Institute on Aging (RO1/AG06456) and UO1/AG09095), Centers for Disease Control and Prevention (R48/ CCR002181), and by the Department of Veterans Affairs (Health Services Research and Development Service). The opinions expressed are those of the authors, and do not necessarily represent the opinions of the sponsoring institutions or funding agencies.

The authors wish to thank Patty Karlen for her dedication, care, and efficiency as study co-ordinator.

*References*

1. Buchner DM, de Lateur BJ. The importance of skeletal muscle strength to physical function in older adults. *Ann Behav Med* 1991;**13**:91–8.
2. Buchner DM, Beresford SAA, Larson EB, LaCroix AZ, Wagner EH. Effects of physical activity on health status in older adults: II. Intervention studies. *Annu Rev Public Health* 1992;**13**:469–88.
3. Young A. Exercise physiology in geriatric practice. *Acta Med Scand* 1986;**suppl.711**:227–32.
4. Buchner DM, Cress ME, Wagner EH, de Lateur BJ. The role of exercise in fall prevention: developing targeting criteria for exercise programs. In: Vellas B, Toupet M, Rubenstein L, Albarede JL, Christen Y, eds. *Falls, balance and gait disorders in the elderly*. Paris: Elsevier, 1992;55–67.
5. Aniansson A, Rundgren A, Sperling L. Evaluation of functional capacity in activities of daily living in 70-year-old men and women. *Scand J Rehabil Med* 1980;**12**: 145–54.
6. Danneskiold-Samsoe B, Kofod V, Munter J, Grimby G, Schnohr P, Jensen G. Muscle strength and functional capacity in 78–81-year-old men and women. *Eur J Appl Physiol* 1984;**52**:310–14.
7. Duncan PW, Chandler J, Studenski S, Hughes M, Prescott B. How do physiological components of balance affect mobility in elderly men? *Arch Phys Med Rehabil* 1993;**74**:1343–9.
8. Bendall MJ, Bassey EJ, Pearson MB. Factors affecting walking speed of elderly people. *Age Ageing* 1989;**18**:327–32.
9. Bassey EJ, Bendall MJ, Pearson M. Muscle strength in the triceps surae and objectively measured customary walking activity in men and women over 65 years of age. *Clin Sci* 1988;**74**:85–9.
10. Fiatarone MA, Marks EC, Ryan ND, Meredith CN, Lipsitz LA, Evans WJ. High-intensity strength training in nonagenarians. *JAMA* 1990;**263**:3029–34.
11. Bassey EJ, Fiatarone MA, O'Neill EF, Kelly M, Evans WJ. Leg extensor power and functional performance in very old men and women. *Clin Sci* 1992;**82**:321–7.
12. Wagner EH, Grothaus LC, Hecht JA, LaCroix AZ. Factors associated with participation in a senior health promotion program. *Gerontologist* 1991;**31**:598–602.
13. Morris-Chatta R, Buchner DM, de Lateur BJ, Cress ME, Wagner EH. Isokinetic testing of ankle strength in older adults: assessment of inter-rater reliability and stability of strength over six months. *Arch Phys Ther Rehabil* 1994;**75**:1213–16.
14. Ferrandez AM, Pailhous J, Durup M. Slowness in elderly gait. *Exp Aging Res* 1990;**16**:79–89.
15. Fiatarone MA, O'Neill EF, Ruan ND, *et al.* Exercise training and nutritional supplementation for physical frailty in very elderly people. *N Engl J Med* 1994;**330**:1769–75.
16. Buchner DM, Cress ME, Esselman PC, *et al.* The effect of strength and endurance training on gait, balance, fall risk, and health services use in community-living older adults. (In press.)
17. Kronmal RA. Spurious correlation and the fallacy of the ratio standard revisited. *J R Stat Soc (A)* 1993;**3**:379–92.
18. Skelton DA, Greig CA, Davies JM, Young A. Strength, power and related functional ability of healthy people aged 65–89 years. *Age Ageing* 1994;**23**:371–7.

*Authors' addresses*

D. M. Buchner, E. B. Larson, E. H. Wagner, T. D. Koepsell
Department of Health Services,

B. J. de Lateur
Department of Rehabilitation Medicine,
University of Washington, Box 358852,
Seattle, Washington 98195-8852, USA

*Received in revised form 10 April 1996*