Etiology and modification of gait instability in older adults: a randomized controlled trial of exercise

Jeffrey M. Hausdorff, Miriam E. Nelson, David Kaliton, Jennifer E. Layne, Melissa J. Bernstein, Andrea Nuernberger and Maria A. Fiatarone Singh

Journal of Applied Physiology 90:2117-2129, 2001.

J Appl Physiol
90: 2117–2129, 2001.

Etiology and modification of gait instability in older adults: a randomized controlled trial of exercise

JEFFREY M. HAUSDORFF,[1] MIRIAM E. NELSON,[2] DAVID KALITON,[1] JENNIFER E. LAYNE,[2] MELISSA J. BERNSTEIN,[2] ANDREA NUERNBERGER,[2] AND MARIA A. FIATARONE SINGH[2,3]
[1]*Gerontology Division, Beth Israel Deaconess Medical Center, and Division on Aging, Harvard Medical School, Boston 02215;* [2]*The Exercise Physiology, Nutrition, and Sarcopenia Laboratory, Jean Mayer United States Department of Agriculture Human Nutrition Research Center on Aging at Tufts University, Boston, Massachusetts 02111; and* [3]*School of Exercise and Sport Science, University of Sydney, Lidcombe, Australia*

Received 23 March 2000; accepted in final form 8 December 2000

Hausdorff, Jeffrey M., Miriam E. Nelson, David Kaliton, Jennifer E. Layne, Melissa J. Bernstein, Andrea Nuernberger, and Maria A. Fiatarone Singh. Etiology and modification of gait instability in older adults: a randomized controlled trial of exercise. *J Appl Physiol* 90: 2117–2129, 2001.—Increased gait instability is common in older adults, even in the absence of overt disease. The goal of the present study was to quantitatively investigate the factors that contribute to gait instability and its potential reversibility in functionally impaired older adults. We studied 67 older men and women with functional impairment before and after they participated in a randomized placebo-controlled, 6-mo multimodal exercise trial. We found that *1*) gait instability is multifactorial; *2*) stride time variability is strongly associated with functional status and performance-based measures of function that have previously been shown to predict significant clinical outcomes such as morbidity and nursing home admission; *3*) neuropsychological status and health-related quality of life play important, independent roles in gait instability; and *4*) improvement in physiological capacity is associated with reduced gait instability. Although the etiology of gait instability in older persons with mild-moderate functional impairment is multifactorial, interventions designed to reduce gait instability may be effective in bringing about a more consistent and more stable walking pattern.

muscle function; aging; plasticity; exercise; dynamics variability

INCREASED GAIT INSTABILITY, marked unsteadiness and inconsistency from one stride to the next, is common in many older adults, even in the absence of overt disease (36, 57, 82). Gait instability predisposes individuals to falls and likely contributes to changes in neuropsychological and functional status, including a fear of falling, decreased confidence, and self-imposed mobility restrictions (Fig. 1) (57, 80, 81). Marked gait instability may also detract from quality of life and lead to functional dependence and institutionalization.

In persons with neurodegenerative (e.g., Parkinson's) disease, deficits in the central nervous system's ability to regulate and coordinate motor outputs are largely responsible for locomotor instability (7, 35, 36, 39, 58, 61). In contrast, in older adults without apparent neurological disease, the reasons for the increased gait instability are less clear. It is likely that they are multifactorial. Physiological deficits secondary to aging and disuse may perturb the locomotor system of the older adult to bring about gait instability (Fig. 1) (2, 36, 57, 82). Many age-associated changes may contribute to this process, including reduced range of motion, decreased aerobic capacity, decreased muscle function, and impaired balance (1, 2, 20, 70, 77). Other factors, such as impaired neuropsychological function, may also heighten instability, further exacerbating the effects of decreased physiological capacity (Fig. 1). However, the interrelationships between gait instability and physiological capacity, neuropsychological status, and health-related quality of life have not been well studied. Few studies have quantitatively examined the effects of these age-associated changes on gait instability, the plasticity of gait instability, or the ability to modify physiological and neuropsychological parameters and improve gait stability (51, 57).

In the present study of gait instability in the elderly, we focus on one of the outputs of the locomotor system: the temporal fluctuations in the gait cycle duration (8, 29, 57, 89). The gait cycle duration, also known as the stride time or the stride interval, reflects the walking rhythm. Because it relies on central and peripheral inputs and feedback, it can be viewed as a final output of the locomotor system. Moreover, because a variety of physiological and neuropsychological systems may impact on stride time dynamics, instability measures may be a sensitive marker of dynamic system integration (8, 29, 35, 38, 57, 61).

Stride-to-stride changes in the gait cycle duration can be described with respect to the fluctuation magnitude (e.g., the variance, the size of the fluctuations) and the fluctuation dynamics (how the stride time

Address for reprint requests and other correspondence: J. M. Hausdorff, Gerontology Div., Beth Israel Deaconess Medical Center, 330 Brookline Ave., Boston, MA 02215 (E-mail: jhausdor@caregroup.harvard.edu).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked "*advertisement*" in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Journal of Applied Physiology

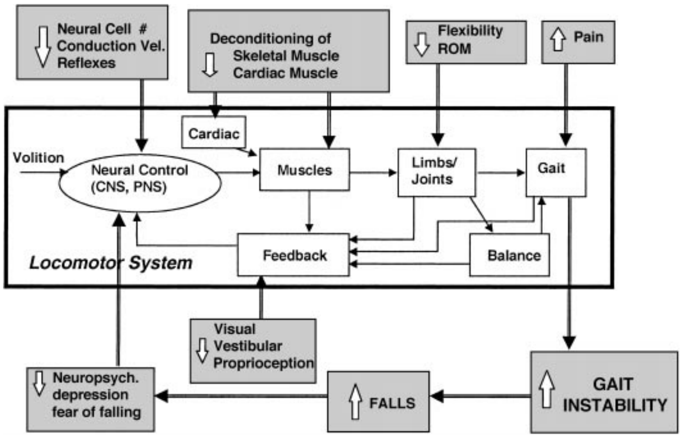

Fig. 1. Simplified block diagram illustrating some of the physiological and neuropsychological factors that may be associated with gait instability. Locomotor system and certain age-associated changes (shaded boxes) in physiological capacity that may mediate gait instability are shown. Goals of the present study were *1*) to quantify the association between gait instability and these potential contributing factors and *2*) to determine whether modification of proximate mediators of gait instability would reduce gait instability. Note the highly interdependent nature of many of these relationships and their putative effect on gait instability. CNS, central nervous system; PNS, peripheral nervous system; ROM, range of motion.

changes from one stride to the next, independent of the variance) (29, 35, 38, 57, 64, 87). Although both aspects may be referred to as gait instability, a priori, different factors may participate in the regulation of the fluctuation magnitude and the fluctuation dynamics, and the clinical relevance of these two aspects of gait instability may be different as well. For example, in healthy older adults, the fluctuation magnitude is similar to that observed in healthy young adults, although there are subtle age-related changes in the fluctuation dynamics (29, 39).

The goals of the present study, therefore, are to quantitatively investigate gait instability, the factors that contribute to it, its relationship to neuropsychological and functional status, and its potential reversibility in functionally impaired older persons. Functional impairment is an important problem in elderly individuals, leading to great personal and societal burden, including clinical sequelae, such as falls and institutionalization (2, 33, 48, 57, 80). A more complete understanding of its complex multifactorial etiology is necessary to design preventive and rehabilitative approaches to this syndrome (2, 60). Functionally impaired elders often present with mobility problems, physiological deficits (balance, strength, endurance, flexibility), and psychosocial problems (2, 10, 80), and therefore all these domains should be assessed when approaching this area of investigation. A common thread among these domains of function and capacity is abnormality of gait characteristics in frail elders. However, gait instability is a characteristic of gait that has been minimally studied in this regard compared with gait velocity and other simpler constructs. There is reason to believe that gait instability may be a more powerful predictor of functional impairment than characteristics that focus on the mean or "typical" value of gait, e.g., average walking velocity (40, 57).

This study was undertaken with two major purposes in mind: *1*) The physical and psychological factors that are associated with gait instability in functionally impaired elders were examined to better understand this element of overall gait and mobility. Understanding its etiology will advance the understanding of the neurophysiological changes associated with aging and the attempts to intervene in this domain and, ultimately, improve function. *2*) The efficacy of a multifactorial intervention designed to improve multiple physical capacities simultaneously, i.e., muscle strength, balance, aerobic capacity, and flexibility, was tested. The elements of this intervention were chosen to specifically target those physical capacities that are known to be impaired with age and also believed to be modifiable with appropriate exercise modalities (12, 26, 62, 92). We hypothesized that modification of the proximate physiological mediators of gait instability would affect the distal outcome, gait instability itself. To this end, we measured gait instability and potential contributing factors in older men and women with functional impairment before and after they participated in a randomized placebo-controlled, 6-mo multimodal exercise trial.

METHODS

Subjects

Older men and women were recruited from the Greater Boston Area to participate in a randomized controlled, 6-mo clinical trial designed to study the effects of home-based exercise on functional status (63). The protocol and consent forms were approved by the Tufts University Human Investigation Review Committee, and all study subjects provided informed written consent. To ensure that the study subjects were functionally impaired but did not have any overt pathology that might affect gait, the following protocol was used. All subjects were ≥70 yr of age and not engaged in a regular exercise program. A two-stage process was employed so that all study subjects were functionally impaired by self-report and as measured using standardized tests of functional performance. Subjects needed to report at least two functional limitations during a telephone prescreen on the physical function subscale of the Medical Outcome Survey (79). If subjects met these initial criteria, they were asked to visit the center. A physician trained in geriatric medicine who was sensitive to the study objectives extensively screened each subject. Included in the examination was a complete medical and physical examination as well blood and urine tests. Subjects with unstable cardiovascular disease, psychiatric disorders, neurological or muscular disease, terminal illness, or cognitive impairment [a score of <23 on the Folstein Mini-Mental State Exam (27)] were excluded from participation. In addition, during the screening process, subjects needed to score ≤10 on the Short Physical Performance Battery (SPPB) (33), a widely used performance-based measure of function, to ascertain moderate-to-marked lower body functional impairment. Five hundred sixty-five potential subjects were screened by telephone. Ninety-four subjects came to our center for a physical examination. Seventy-two subjects were randomized to the study, and 70 subjects completed the interventions. We measured gait instability in 67 of these subjects at baseline; postmeasures were available in 64 subjects. In these subjects, we also evaluated all domains that may affect gait, including cognition, depression, perceived quality of life, physical activity levels, exercise capacity, strength, flexibility, and endurance. All baseline and final (6 mo) testing was carried out at the Jean Mayer US Department of Agriculture Human Nutrition Research Center on Aging at Tufts University.

Assessments

Gait instability. The protocol and analytic methods were similar to those employed previously to study gait instability in neurological disorders (35, 39). Subjects were instructed to walk on level ground at their normal pace around a 91.4-m-long indoor carpeted pathway for 2 min. To measure the gait rhythm and the timing of the gait cycle, force-sensitive insoles (37) were placed in the subject's shoe. These inserts produce a measure of the force applied to the ground during ambulation. A small, light-weight (5.5 × 2 × 9 cm, 0.1 kg) recorder was worn on each ankle. Subsequently, the digitized data were transferred to a workstation for analysis using software that extracts the initial contact time of each stride (37). With this information, the stride time or duration of the gait cycle (time from initial contact of one foot to subsequent contact of same foot) was determined for each stride during the 2-min walk, and a time series of stride times was generated for each subject. As we now describe, several measures were used to quantitatively assess different aspects of the stride-to-stride fluctuations in each subject's stride time (35, 39, 41).

Fluctuation magnitude. To study the intrinsic dynamics of the gait rhythm, the time series of the stride time was analyzed as follows (35, 39, 41). The first 5 s of the recorded data were excluded to minimize any start-up effects, and then a median filter was applied to remove data points that were 3 SDs greater than or less than the median value. The average stride time was determined, and a measure of stride-to-stride variability (fluctuation magnitude) was calculated. The stride time variability is defined here as the stride time coefficient of variation (CV), where the variability is normalized to each subject's mean stride time (CV = 100 × SD/mean).

Fluctuation dynamics. We quantified the temporal "structure" or ordering of each time series (independent of the overall variance) by calculating two measures of the stride time fluctuation dynamics: the nonstationary index and the inconsistency of the variance (38). Two time series can be very similar with respect to the mean and variance, i.e., the fluctuation magnitude, but may change in time in different ways and have different fluctuation dynamics (see http://reylab.bidmc.harvard.edu/DynaDx/index.html). To minimize the effects of any differences in mean or variance, each time series was first normalized with respect to its mean and SD, yielding new time series each with mean = 0 and SD = 1, but with different dynamic properties depending on how the local values change with time (38). This normalized time series was then divided into blocks of five strides each, and in each segment the (local) average and (local) SD were computed. The nonstationary index, defined as the SD of the local averages, was then calculated to estimate the dispersion of these normalized, local means. The nonstationary index provides a measure of how the local average values change during the walk, independent of the overall variance (the fluctuation magnitude) of the original time series. A higher nonstationary index indicates greater range among the local averages. We also calculated the inconsistency of the variance, the SD of the local SDs, to evaluate how the local SD changes with time. Higher inconsistency of the variance values indicates greater dispersion and more inconsistent local SDs; the normalized variance is "unstable" and fluctuating with time. Compared with healthy controls (38), the nonstationary index is decreased in subjects with advanced Huntington's disease, while the inconsistency of the variance is increased. The nonstationary index and the inconsistency of the variance are unitless. A composite instability index was next constructed by combining the stride variability and the inconsistency of the variance after normalizing each to a 0–1 scale, with 0 corresponding to low instability. If gait instability changes in the present study subject are parallel to those seen in Huntington's disease, one would anticipate that the nonstationary index would be relatively decreased in persons with greater dysfunction, while the stride time variability, the inconsistency of the variance, and the composite instability index would be relatively increased in persons with greater levels of impairment.

Demographics, health, and neuropsychological status. Standardized tests were used to evaluate baseline status and to control for any group differences. As described below, all the tests were previously validated and have been shown to be reliable and sensitive to change in elderly populations. The number of chronic diseases was ascertained by the study physician through the physical examination and a review of the medical history. On the day of screening, subjects brought in all prescription and over-the-counter medications taken on a consistent basis (at least once a week) to establish the total number of medications used regularly. The Mini-Mental State Exam (27) was used to estimate cognitive impairment. This test has been used extensively to assess mental function in various geriatric populations (28, 31, 43). The Geriatric Depression Scale (GDS), a 30-item yes/no questionnaire with scores ranging from 0 to 30, was used to quantify depressive symptoms (93). The GDS is a reliable and valid self-rating depression screening scale for elderly populations (93). Physical activity levels were estimated from the Physical Activity Scale for the Elderly (PASE) (85). Higher scores correspond to greater levels of activity. PASE scores have been shown to be positively associated with grip strength, static balance, and leg strength and negatively correlated with resting heart rate, age, and perceived health status, with test-retest reliability, assessed over a 3- to 7-wk interval, of 0.75 (95% confidence interval = 0.69–0.80) (85).

Functional status and health-related quality of life. Self-report of the ability to perform activities of daily living (ADLs) and instrumental ADLs (IADLs) were assessed using the Katz ADL and Lawton IADL questionnaires (50, 53). Higher scores on the Lawton IADL correspond to greater functional ability, and lower scores on the Katz ADL correspond to greater functional ability. These instruments are often included in geriatric assessments and have been shown to correlate with depressive symptoms, confidence in avoiding falls while performing usual activities, and physical measures such as gait velocity, balance function, and grip strength (45, 67, 80, 86).

The physical performance test (PPT) was used as a direct observation measure of multiple domains of physical function (73). A maximum score of 36 is possible on the PPT, which includes tests such as lifting a book and putting it on a shelf, putting on and removing a jacket, picking up a penny from the floor, turning 360°, a 50-foot walk test, and climbing stairs. The SPPB was used as a direct measure of lower extremity function. It measures three different functions: balance by tandem stand, strength and transferring skill by chair stands, and mobility by walking (33). A maximum score

Journal of Applied Physiology

of 12 is possible on the SPPB. On both tests, higher scores correspond to better function. The SPPB has been shown to predict risk for mortality and nursing home admission and is also strongly associated with depressive symptoms and self-report of disability (33, 66). The PPT has been shown to be reliable (Cronbach's $\alpha = 0.87$, interrater reliability = 0.99) and has demonstrated concurrent validity with self-reported measures of physical function, cognitive status, and mental health (32, 72, 73). Specifically, scores on the PPT are highly correlated (0.50–0.80) with modified Rosow-Breslau, IADL, and ADL scales and Tinetti's Performance-Oriented Assessment gait score (72).

Fall status was determined by asking subjects if they had experienced any falls (13) in the last 12 mo.

The Medical Outcomes Survey Short Form (SF-36) was used to evaluate eight domains of perceived health-related quality of life (79): physical functioning, role-physical, bodily pain, general health, vitality, social functioning, role-emotional, and mental health. Scores in each domain can range from 0 to 100, with higher scores reflecting better quality of life. The SF-36 is a validated tool for assessing general, physical, and mental health and social and role functioning with reported reliability of 0.81–0.88 (79).

Physiological capacity. MUSCLE FUNCTION. The one repetition maximum (1 RM) was used to measure dynamic concentric muscle strength of the legs, arms, and trunk using the knee extension, double leg press, and lateral pull-down machines (Keiser Sports Health Equipment, Fresno, CA). The 1-RM test has been widely used to evaluate muscle function and the ability of the muscle to generate force in various populations (25, 47, 59, 62). In older adults, reproducibility of the 1 RM is high, with a high correlation between repeat measures 1 wk apart (62). To determine the 1 RM, incremental loads were added until failure occurred despite verbal encouragement to exert maximal effort (26, 62). Knee extension endurance was measured by determining the total number of repetitions achieved with proper form and no pauses at 90% of the 1 RM. Maximal leg extensor power was also determined using a double-leg-press machine (Keiser Sports Health Equipment). Maximal hand grip strength was determined using a hand grip dynamometer (Takei Scientific Instruments). Reduced grip strength, a validated measure of upper extremity strength, is a strong predictor of disability in older people and is also associated with increased risk of mortality in acute illness (19, 30, 68, 71). The highest of three measurements was used for maximal grip strength.

EXERCISE CAPACITY. The 6-min walk test, a submaximal estimate of cardiorespiratory fitness (6, 54), was used to estimate exercise capacity. Subjects were asked to walk as fast as possible for 6 min, with verbal encouragement given every 30 s, and the distance covered was measured (Redi Measure, Redington, Windsor, CT). The 6-min walk test is reliable in this population, with a 1-wk test-retest reliability of 0.95; it is a strong predictor of peak oxygen consumption during exercise and cardiac morbidity, has been shown to be a valid measure of exercise and aerobic capacity, and is correlated with other submaximal exercise tolerance tests, such as bicycle ergometery and treadmill walking (16, 34, 52).

BALANCE. Balance was measured with a variety of static and dynamic tests. Tandem and one-legged stance times were measured to the nearest 0.1 s to assess static balance. For tandem stance, subjects were asked to stand with the heel of one foot directly in front of the toes of the other foot for a maximum of 30 s. For one-legged stance, subjects were asked to stand on their preferred leg for a maximum of 30 s. The amount of time until the subject moved from the tandem position or put the other foot down, moved the foot on the floor, or touched any object with his/her hand to maintain balance was used for the measurement end point. These measures of balance have been correlated with force platform-based indexes of postural control as well as with physical function, have high test-retest reliability, and because they can be readily assessed outside a balance laboratory, have been widely used to quantify balance in the elderly (1, 12, 13, 18, 42, 44, 65, 75).

The Functional Reach Test was used to further assess static balance. Using a yardstick placed at shoulder height, subjects were asked to reach as far forward as possible in a plane parallel with the yardstick without taking a step. Subjects were given two practice trials. Their performance during an additional three trials was recorded, and the results were expressed as the best of the three trials. During any trial, if the base of support (feet) moved, data were discarded and the trial was repeated (22). Functional reach is a validated measure of balance; it correlates with walking speed, one-legged stance time, dynamic balance, and IADLs and has been associated with fall risk (21, 22, 84, 86).

Dynamic balance was assessed using the timed forward tandem walk test over a 20-foot course. The subject was instructed to place one foot in front of the other, making sure that, with each step, the heel of one foot was directly in front of the toes of the other foot. The subject was told to walk forward as fast as possible without falling or making any mistakes. The average time recorded to the nearest 0.1 s during two trials was used in the analysis. In addition to time, the number of mistakes (misplacement of steps) was also recorded (62). The reproducibility of balance measured in this way is high in this population, with significant correlation between repeat measurements 1 wk apart ($r = 0.94$, $P = 0.001$) (62). A composite measure was calculated by summing the time and the number of mistakes, with higher scores indicating worse performance, i.e., more compromised balance.

Gait speed. Maximal and habitual gait speed were assessed over the middle 2 m of a 4-m course with an ultrasonic timer (Ultratimer, DCPB Electronics, Glasgow, Scotland). The average of two measurements made to the nearest 0.01 s was used to determine the maximal and habitual gait speed. Gait speed is a commonly used, reliable measure of physical function in geriatric patients and is a valid indicator of ADL function and lower extremity strength (11, 14, 69, 78).

Flexibility. As performed as part of standard physical therapy practice, passive ankle dorsiflexion and plantarflexion ranges of motion were measured using a goniometer, standardized bony landmarks, and positions.

Upper extremity/shoulder flexibility (back reach) was assessed by measuring the distance between the thumbs as the subject reaches behind the back. The right upper extremity was flexed, abducted, and externally rotated at the shoulder and flexed at the elbow while the left upper extremity adducted, internally rotated, and extended at the shoulder and flexed at the elbow, with both hands placed in close proximity. This measure was repeated with each extremity in opposite positions, and the better of these two measures was used, with a lower number corresponding to greater flexibility. A second measure of upper extremity flexibility, shelf reach, was assessed by measuring the height the subject could reach up to a shelf (73).

Interventions

Exercise group. Subjects in the exercise group were given a 6-mo, home-based exercise program that focused on progressive strength and balance training with encouragement to increase overall aerobic and physical activity (63). The exercise program was designed *1*) to follow the standards and target levels recommended by the American Council for Sports Medicine; *2*) to modify three major components of physical capacity that have been related to function and mobility: strength, balance, and exercise capacity; *3*) to mimic, to the degree possible, the laboratory-based interventions that successfully improved strength, balance, and function in similar populations; *4*) to be simple to learn and performed by functionally impaired older adults at home; and *5*) to provide opportunities for increasing the intensity of the exercise and a range of levels (12, 26, 46, 62, 63). An exercise trainer came to the home to instruct the subject on how to safely and properly perform the exercises. During the first home visit, each subject was given a detailed booklet outlining the program, several sets of dumbbells, and a pair of 20-pound adjustable ankle weights (AllPro Equipment, Jericho, NY). The ankle weights were adjustable from 1 to 20 pounds, in 1-pound increments (we note that none of the subjects "maxed" out). Six home visits were conducted over the 1st mo, with one home visit each month thereafter. The exercises were as follows: chair stands (3 levels from using hands to no hands), circle turns (3 levels), tandem walk (3 levels), plantarflexion (3 levels), ankle dorsiflexion, knee extension (with ankle weights), standing hip extension (with ankle weights), standing hip abduction (with ankle weights), overhead raise (dumbbells), biceps curl (dumbbells), and triceps extension (dumbbells). The upper extremity exercises were included because flexibility and upper extremity strength may impact on function and gait. Subjects were asked to perform the balance and strength exercises three times per week. To tailor the intervention "dose" to each individual, two sets of eight repetitions for each exercise were performed at a target-relative, perceived exertion of 7–8 on the 10-point Borg scale (9). This target level is parallel to that used in laboratory, machine-based studies of progressive resistance training, where the exercise level is at 80% of the 1 RM and is based on American College of Sports Medicine recommended practice and our previous successful experiences in work with older adults (25, 26, 59, 62). Every 2 wk, subjects were encouraged to increase the level of weight at which they were working to maintain the proper intensity and to ensure adequate dose. Subjects were also asked to accumulate 30 min of aerobic activities such as walking and stair climbing each day. All physical activities were documented in exercise logs that were returned to the investigators each month.

Attention control group. Subjects in the attention control group received 6 mo of nutrition education. A registered dietitian made four home visits to each attention control subject in the 1st mo of study and one home visit per month thereafter. As with the exercise group, attention control subjects were given logs to be filled out daily to keep track of the number of servings of fruits, vegetables, and calcium-rich foods consumed.

Statistical Analysis

Univariate and multivariate regression analyses were used to assess the relationship between gait instability measures and potential contributing factors. Comparisons of the baseline characteristics of the subjects in the two groups were analyzed using Fisher's exact test and χ^2 test for categorical data and Student's *t*-test for continuous data. Data were inspected for normality before use in regression and analysis of covariance models. Variables that were associated with a gait instability measure ($P < 0.10$) in univariate analysis were included as inputs to multivariate models. Pearson's and Spearman's correlation coefficients were used to quantify univariate associations, as indicated. To study the effects of exercise on the gait instability measures, repeated-measures ANOVA was applied to each of the gait instability measures. Age, gender, and any measures that tended to be different ($P < 0.10$) in the two groups in univariate analysis were included as covariates to determine the effect of the intervention on each gait instability measure after adjustment for any possible group differences. $P = 0.05$ (2-sided) was used as the level of significance. Unless indicated otherwise, group results are reported as means ± SD. Statistical analysis was performed using SAS software (release 7, SAS, Cary, NC).

RESULTS

Subject Characteristics

Table 1 summarizes the subjects' characteristics. Subjects were predominantly female, in their 70s and 80s, had several chronic conditions, and were taking several medications. Cognitive status was normal, but there was a range of depressive symptoms. Functional impairment was generally mild to moderate, as measured by self-report and performance-based measures. There was a wide range of health-related quality of life and physiological capacity at baseline.

Before the intervention, there was a wide range of gait instability among the study subjects (Table 1). Stride time variability ranged from 1.6 to 10.4%. The average stride time variability was 3.6%, almost twice that seen in healthy young and older adults (29, 39). The two measures of the stride time dynamics, the nonstationary index and the inconsistency of the variance, ranged from 0.31 to 0.93 and from 0.11 to 0.45, respectively. Measures of the fluctuation dynamics, the nonstationary index and the inconsistency of the variance, were not correlated with the fluctuation magnitude (stride time variability) but were moderately correlated with one another (Pearson's $r = -0.59$, $P < 0.0001$).

Baseline Predictors of Gait Instability

All measures of gait instability were similar in men and women ($P > 0.47$). Stride time variability was larger among subjects who reported having fallen two or more times in the 12 mo before baseline ($n = 11$) than among the other subjects (4.7 ± 2.2 vs. 3.4 ± 1.6%, $P = 0.020$).

The baseline univariate predictors of gait instability are shown in Table 2. Increased stride time variability generally indicated dysfunction in other domains. For example, high variability was associated with decreased functional status (self-report and performance based), decreased health-related quality of life (i.e., lower physical function and vitality), reduced neuropsychological status (i.e., increased depressive symptoms), decreased physiological capacity (e.g., reduced exercise capacity, dynamic balance, and functional reach), lower physical activity levels, and lower health status [i.e., increased body mass index (BMI)]. Similar

Table 1. *Subject characteristics at baseline*

	Means ± SD	Range
	Demographics, neurophysiological and health status	
Age, yr	77.7 ± 5.3	70–92
%Women	78%	
BMI, kg/m²	28.7 ± 5.5	19.8–45.5
Chronic conditions, *n*	3.5 ± 1.6	0–8
Medications, *n*	3.2 ± 2.5	0–10
Cognitive status (Mini-Mental State Exam)	28.7 ± 1.2	25–30
Depressive symptoms, GDS score	5.5 ± 4.2	0–16
Physical activity level, PASE	61.4 ± 39.7	2.2–156.3
	Functional status	
ADLs (Katz)	6.3 ± 0.5	6–8
IADLs (Lawton)	23.0 ± 1.3	18–24
PPT	27.9 ± 4.2	13–34
SPPB	7.5 ± 2.2	2–11
	Quality of life (SF-36)	
Physical-function	65.7 ± 19.2	10–95
Role-physical	61.6 ± 37.0	0–100
Health	69.9 ± 16.8	20–97
Vitality	55.4 ± 20.8	0–95
Mental	81.4 ± 14.5	40–100
Emotional	85.1 ± 29.7	0–100
Social	86.6 ± 18.8	25–100
Bodily pain	65.4 ± 21.2	21–90
	Exercise capacity, gait, balance, flexibility	
Knee extension 1 RM, N	167.5 ± 62.9	66.0–435.9
Knee extension endurance, no. of reps @ 90% of 1 RM	3.1 ± 1.4	1–10
Leg press 1 RM, N	344.6 ± 133.0	151–798
Leg power, W	105.1 ± 78.7	21.9–363.3
Lateral-pull-down 1 RM, N	132.6 ± 44.7	57.3–245.5
Hand grip strength, kg	21.1 ± 7.4	7.8–44.7
Exercise capacity (6-min walk distance), m	379.9 ± 105.2	155.1–549.2
Functional reach, cm	84.9 ± 16.5	12.7–113.0
Dynamic balance*	57.7 ± 17.0	27.4–119.6
One-legged stance time, s	5.4 ± 6.9	0.4–30.0
Tandem stance time, s	12.5 ± 10.8	0.6–30.0
Habitual gait speed, m/s	0.98 ± 0.24	0.30–1.44
Maximal gait speed, m/s	1.36 ± 0.33	0.52–1.94
Stride time, ms	1180 ± 157	916–1792
Shelf reach, cm	35.3 ± 11.3	14.0–65.5
Back reach, cm	15.8 ± 10.0	3.5–75.0
Dorsiflexion, degrees	3.2 ± 5.2	−20–17
Plantarflexion, degrees	49.0 ± 10.2	23.0–72.0
	Gait instability	
Stride time variability, %	3.6 ± 1.8	1.6–10.4
Nonstationary index	0.66 ± 0.12	0.31–0.93
Inconsistency of the variance	0.31 ± 0.07	0.11–0.45
Composite instability index	0.82 ± 0.28	0.28–1.79

In the Mini-Mental Status Exam, possible score is 0–30; higher is better. Quality of life (SF-36) data reflect results from 8 domains of the Medical Outcomes Survey (79). Possible scores on the SF-36 range from 0 to 100, with higher scores indicating better quality of life. Possible scores on activities of daily living (ADLs; lower score better) and independent ADLs (IADLs; higher score better) range from 6 to 18 and from 8 to 24, respectively. *Average time to complete the walking test was 46.1 ± 13.7 s; the number of mistakes observed was 11.7 ± 5.4. BMI, body mass index; GDS, Geriatric Depression Scale (possible score 0–30; higher is worse); PASE, Physical Activity Scale for the Elderly (possible score 0–400; higher is better); PPT, physical performance test; SPPB, short physical performance battery; RM, repetition maximum.

Table 2. *Univariate predictors*

	r	*P*
	Stride time variability	
Stride time*	0.77	0.0001
PPT	−0.70	0.0001
Exercise capacity (6-min walk distance)	−0.66	0.0001
Habitual gait speed	−0.65	0.0001
Maximal gait speed	−0.59	0.0001
Physical function (SF-36)	−0.57	0.0001
SPPB	−0.53	0.0001
IADL	−0.49	0.0001
ADL*	0.44	0.0002
Functional reach	−0.33	0.007
Vitality (SF-36)	−0.32	0.008
Depressive symptoms (GDS)	0.31	0.010
Physical activity level (PASE)	−0.30	0.016
Dynamic balance*	0.29	0.023
BMI*	0.26	0.037
Shelf reach*	−0.26	0.033
Age	0.25	0.041
Leg power	−0.25	0.056
	Nonstationary index	
Vitality† (SF-36)	0.34	0.005
Health (SF-36)	0.33	0.006
Chronic conditions† (*n*)	−0.31	0.012
Maximal gait speed†	0.29	0.018
Depressive symptoms	−0.27	0.025
Habitual gait speed	0.24	0.055
Physical function (SF-36)	0.24	0.055
Tandem stance time	0.23	0.059
	Inconsistency of the variance	
Vitality (SF-36)	−0.32	0.008
Health‡ (SF-36)	−0.30	0.013
Bodily pain‡ (SF-36)	−0.30	0.014
Physical function (SF-36)	−0.29	0.018
Depressive symptoms (GDS)	−0.27	0.026
Social (SF-36)	−0.24	0.050
Lateral pull-down strength‡	−0.24	0.058
	Composite instability index	
Stride time§	0.66	0.0001
Physical function (SF-36)	−0.61	0.0001
PPT	−0.60	0.0001
Exercise capacity (6-min walk distance)	−0.57	0.0001
Habitual gait speed	−0.54	0.0001
Maximal gait speed	−0.52	0.0001
IADL	−0.49	0.0001
SPPB	−0.48	0.0001
ADL	0.45	0.0001
Vitality§	−0.45	0.0001
Depressive symptoms (GDS)	0.41	0.0005
BMI	0.30	0.017
Health (SF-36)	−0.30	0.014
Bodily pain (SF-36)	−0.29	0.017
Tandem stance time§ (static balance)	−0.26	0.035
Lateral pull-down strength§	−0.25	0.041
Social§ (SF-36)	−0.24	0.046

r, Pearson correlation coefficient. *Significantly related to stride time variability in multivariate analysis. Back reach and the number of chronic conditions were significantly related to stride time variability in multivariate analysis, but not in univariate analysis. †Significantly related to the nonstationary index in multivariate analysis. ‡Significantly related to the inconsistency of the variance in multivariate analysis. Tandem stance time also was related to the inconsistency of the variance in multivariate analysis. §Significantly related to the composite instability index in multivariate analysis.

relationships were observed for the composite instability index.

Both measures of the stride time fluctuation dynamics were associated with health-related quality of life and neuropsychological status (Table 2). The nonstationary index was higher with self-report of better health status, vitality, and physical function, fewer chronic conditions, increased physiological capacity (e.g., gait speed), and fewer depressive symptoms. A lower inconsistency of the variance was associated with higher health-related quality-of-life measures and fewer depressive symptoms and tended to be correlated with increased upper extremity strength. None of the measures of gait instability were significantly correlated with the number of medications (despite a wide range) or mental status (which was confined to a relatively small range).

Multivariate analysis was performed to identify the independent predictors of the different gait instability measures. As noted in Table 2, the independent predictors of stride time variability were average stride time, flexibility (shelf reach and back reach), dynamic balance, health status (number of chronic conditions), functional status (ADLs), and BMI. These factors explained 77% of the variance in stride time variability.

Independent predictors of the nonstationary index were vitality, maximal gait speed, and the number of chronic conditions, explaining 19% of the variance. Independent predictors of the inconsistency of the variance were upper extremity strength, body pain, balance (i.e., tandem stance time), and self-report of health status (SF-36), accounting for 27% of the variance. The independent predictors of the composite instability index were stride time, upper extremity strength, self-report of vitality, and functional status (ADLs), explaining 61% of the variance.

Effects of Exercise

At baseline, the exercise (n = 30) and control (n = 37) groups were similar with respect to gait instability, age, gender distribution, number of chronic conditions, medication usage, BMI, mental status, depressive symptoms, muscle function, gait speed, one-legged and dynamic balance, and flexibility.

Functional status and physiological capacity. The effects of the exercise on functional status and physiological capacity are described in detail elsewhere (63). Briefly, compared with the control group, the exercisers significantly improved dynamic balance and performance-based measures of functional status after participating in the 6-mo, multimodal exercise program. Scores on the PPT increased by 6 ± 14% in the exercisers and decreased by 3 ± 14% in the control group ($P < 0.01$). Scores on the SPPB improved by 28 ± 38% in the exercise group and decreased by 2 ± 22% in the control group ($P < 0.001$). Dynamic balance improved by 32 ± 16% in the exercisers compared with 9 ± 25% in the control group ($P < 0.001$). However, although all measures of physiological capacity tended to improve in the exercisers, there was no significant group × time effect on any measure of strength, muscle endurance, exercise capacity, or habitual or maximal gait speed. For example, knee extension strength was 170 ± 62 and 165 ± 64 N at baseline in the exercise and control groups, respectively, and increased to 200 ± 75 and 183 ± 71 N, respectively, after the intervention. There were also no differences between the groups over time for the self-reported quality-of-life measures (SF-36) or depressive symptoms.

Gait instability outcomes. As shown in Table 3, there was a small, but significant, exercise effect on the inconsistency of the variance and the composite instability index; both measures decreased in the exercise group and increased in the control group. Changes in stride time variability and the nonstationary index in response to the exercise intervention were more variable and were not statistically significant.

An example of the effects of exercise on gait instability is shown in Fig. 2. For this subject with relatively large gait instability at baseline, the stride time variability decreased by ~50% (from 7.6 to 4.0%) after 6 mo of exercise training. The inconsistency of the variance also decreased from 0.46 to 0.31, and the nonstationary index increased from 0.31 to 0.72. The composite index decreased from 1.7 to 0.9. In this subject, knee extension strength also improved by 42% (from 159 to 225 N) in response to the intervention.

Correlates of change in gait instability in response to exercise. Compared with baseline values, a decreased inconsistency of the variance was significantly associated with increased upper extremity flexibility (decreased back reach distance) among the exercisers (Table 4) but not in the control group. In turn, increased upper extremity flexibility (decreased back reach) was associated with decreased depressive symptoms (Spearman's r = 0.42, P = 0.021) and increased functional performance (Spearman's r = −0.34, P = 0.06 with respect to ADL score) in this group. Among the exercisers who showed an improvement in upper extremity flexibility after the intervention (n = 15), the

Table 3. *Effects of exercise on gait instability measures*

	Exercise			Control			
	Baseline	Final	Change	Baseline	Final	Change	P
Stride time variability, %	3.7 ± 2.1	3.3 ± 1.1	−0.4 ± 1.4	3.5 ± 1.5	3.4 ± 1.5	−0.1 ± 1.0	0.324
Nonstationary index	0.67 ± 0.11	0.67 ± 0.11	−0.01 ± 0.15	0.65 ± 0.13	0.63 ± 0.12	−0.03 ± 0.15	0.227
Inconsistency of the variance	0.32 ± 0.07	0.29 ± 0.06	−0.03 ± 0.10	0.31 ± 0.07	0.33 ± 0.07	0.03 ± 0.08	0.007
Composite instability index	0.86 ± 0.35	0.72 ± 0.17	−0.14 ± 0.36	0.78 ± 0.21	0.86 ± 0.21	0.07 ± 0.20	0.002

Values are means ± SD. P values are based on repeated-measures ANOVA controlling for age and gender.

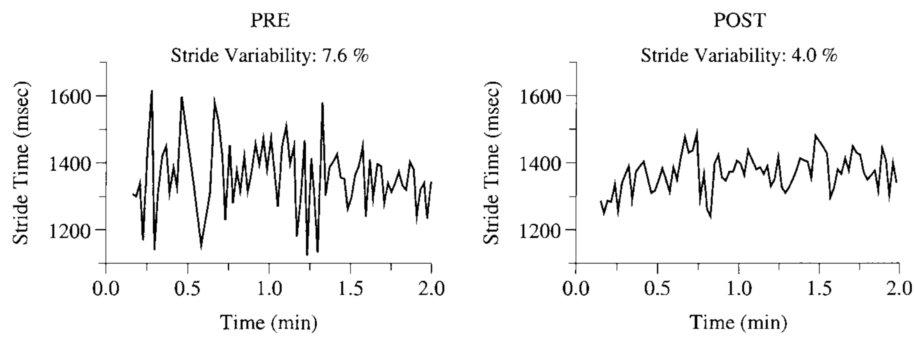

Fig. 2. Effect of exercise on gait instability. In this 75-yr-old woman with relatively large gait instability at baseline, stride time variability (coefficient of variation) decreased by ~50%, from 7.6 to 4.0%, and the other gait instability measures also improved (see text) as knee extension strength improved by 42% after the intervention.

inconsistency of the variance was reduced by 22%, while it increased by 13% in the exercisers who showed no improvement in back reach (P = 0.004).

Changes in stride time variability and the nonstationary index were associated with changes in functional status and physiological capacity. After the intervention, a decreased stride time variability was significantly associated with increased knee extension strength, a better score on a performance-based measure of functional status (PPT), and increased self-report of physical function (SF-36) among the exercisers (Table 4). Change in stride time variability was not associated with these measures in the control group. Similarly, among exercisers who increased knee extension strength (n = 19), stride time variability decreased by 10% after the intervention, while it increased by 13% in exercisers who did not improve knee extension strength (P = 0.037; Fig. 3). Before the intervention, stride time variability was relatively increased in those exercisers who subsequently improved knee extension strength (4.2 ± 2.4 vs. 2.8 ± 0.6, P = 0.032), but after the intervention, stride time variability was similar in both subgroups of exercisers (3.4 ± 1.2 vs. 3.2 ± 1.0, P = 0.75). In other respects, these two subgroups were similar at baseline. This reduction in stride time variability was associated with the improvement in strength (Pearson's r = −0.45, P = 0.014).

These results suggest that instability measures may be more readily modifiable in persons with relatively poor physiological capacity. To study this further, we stratified all subjects on the basis of their baseline habitual gait speed (i.e., normal ≥1.0 m/s; slow <1.0 m/s). The exercise effect on the inconsistency of variance and the composite index persisted among those subjects with relatively slow gait speed ($P < 0.05$) but not among subjects with more normal gait speeds. The exercise intervention had no significant effect on gait speed (habitual and maximal) in subjects with slow or normal gait speed.

After the intervention, an increased nonstationary index was associated with increased ankle range of motion (plantar- and dorsiflexion) and increased exercise capacity among the exercisers (Table 4). Viewed alternatively, the nonstationary index increased by 16% among exercisers who improved dorsiflexion after

Table 4. *Associations between changes in gait instability measures (from baseline to postexercise) and changes in potential covariates*

	Knee Extension Strength (1 RM)	PPT	Physical Function (SF-36)	Knee Extension Endurance
Stride time variability	−0.47 (0.009)	−0.47 (0.009)	−0.46 (0.012)	−0.37 (0.056)
	Plantarflexion	Exercise Capacity	Dorsiflexion	SPPB
Nonstationary index	0.40 (0.032)	0.38 (0.041)	0.36 (0.052)	0.35 (0.058)
	Back Reach			
Inconsistency of the variance	0.46 (0.013)			
	BMI	Back Reach		
Composite instability index	0.43 (0.021)	0.42 (0.026)		

Values are Spearman correlation coefficients among the exercisers; P values are in parentheses. Similar results were obtained using Pearson's correlation.

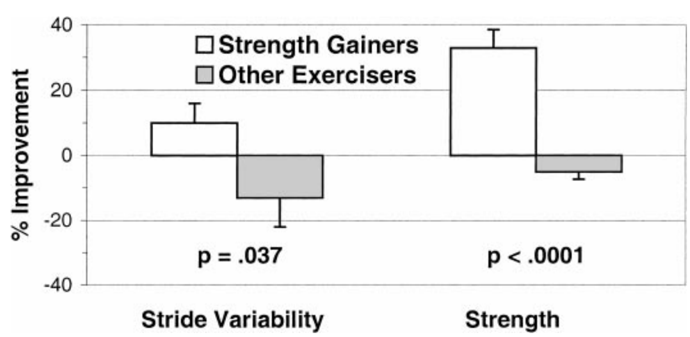

Fig. 3. Among the exercisers, subjects who showed any improvement in knee extension strength (strength gainers) significantly improved knee extension strength and stride variability after the intervention compared with those exercisers who showed no improvement in knee extension strength (other exercisers). Strength and all other measures were not different in these two subgroups of exercisers at baseline, except stride time variability was increased in those subjects who subsequently improved knee extension strength (P = 0.032). The improvement in stride time variability was associated with the improvement in strength (Pearson's r = 0.45, P = 0.014). For stride time variability, improvement here is defined as the negative of the percent change from baseline. Error bars, SE.

Journal of Applied Physiology

the intervention, while it decreased by 8% among the other exercisers ($P = 0.036$).

DISCUSSION

This quantitative study of gait instability in older persons reveals several findings of interest: *1*) Many factors contribute to gait instability. *2*) Stride time variability is strongly associated with self-report of functional status and performance-based measures of function that have been shown to predict important clinical outcomes [e.g., morbidity and nursing home admission (33)]. *3*) Neuropsychological status and health-related quality of life play important, independent roles in gait instability. *4*) Improvement in physiological capacity is associated with reduced gait instability. Taken together, these findings suggest that although the etiology of gait instability in older persons with mild-moderate functional impairment is multifactorial, exercise interventions designed to reduce gait instability may be effective in bringing about a more consistent and more stable walking pattern. To some degree, the age-associated increase in gait instability is modifiable.

The multifactorial nature of gait instability is not surprising. Gait dynamics are controlled by an array of physiological and neuropsychological systems that rely on neural, motor, sensory, and volitional inputs. On the other hand, the strong association between stride time variability and functional status, even with measures that are based on the ability to independently perform activities such as bathing and dressing, is less intuitive. Perhaps this can be better understood by examining the relative importance of balance and muscle function in gait instability. Although gait instability is intuitively linked to balance and balance capabilities are required for walking-related tasks (3), static balance was not a particularly strong predictor of any of the gait instability measures. Similarly, although lower extremity muscle function is certainly important for locomotion (46, 90, 92), in the present study, depressive symptoms were more closely associated with stride time variability than muscle function, and vitality was the most significant predictor of the metrics of gait instability that were based on fluctuation dynamics. Upper extremity function and flexibility also played a relatively critical role in predicting gait instability, consistent with other findings of the importance of these properties on gait. Thus many diverse factors apparently can contribute to gait instability. Perhaps the strong association with functional status and the ability to perform ADLs reflects a common reliance on a multiplicity of neuropsychological and physiological components. Similarly, in studies of community-living older adults (10, 24, 51), it was observed that lower extremity strength explains only a relatively modest amount of the variance of functional performance, highlighting the importance of other factors, in addition to strength, on function and, apparently, gait instability.

Two other factors may partially explain the significance of neuropsychological function and perceived health-related quality of life compared with strength and balance in gait instability in the present study. In general, many physiological systems that participate in walking are not fully taxed but are used only at submaximal levels. For example, only ~40% of maximal strength of the quadriceps is used during habitual ambulation. Similarly, in a study of relatively disabled older women, Ferrucci et al. (24) observed that strength is associated with lower extremity function, mainly in the lower portion of the range of strength, resulting in a curvilinear relationship between physiology and function (14). Thus mild weakness, such as that seen in our subjects, may not show a dramatic effect on gait instability. In addition, it is possible that, with only mild physical impairment, the effects of neuropsychological function become relatively exaggerated. To investigate this question further, it would be helpful to study these relationships among frail older adults with more reduced physiological capacity and to examine the role of conscious effort in the presence of reduced automaticity of function. Nonetheless, it is important to keep in mind that improvement in strength was indeed associated with reduced gait instability.

A number of studies have examined the effects of exercise on gait in older adults (12, 46, 55, 83, 91, 92). Different results have been obtained, in part, because of differences in the exercise intervention, in the study population, in the duration of the exercise program, in the study design, and in the assessment of gait. In a 12-wk randomized trial of dynamic resistance training using elastic tubing (83), significant exercise-related improvement in balance or gait was not achieved. In that study, baseline measures of habitual gait speed were >1 m/s. In another study (91), 12 wk of balance and strength training did not improve gait speed, presumably because baseline strength and balance were already adequate for gait and walking speed was already fairly high (>1 m/s) at baseline, while measures of balance did improve. In contrast, Judge et al. (46) and Lord et al. (55) found significant exercise-related increases in habitual gait speed after 12 wk of balance and strength training and after 22 wk of balance, strength, aerobic, and flexibility training, respectively. In both of these studies, subjects who walked more slowly initially showed the greatest gains in gait speed. In addition, Lord et al. found that, after 12 mo of participation in a multimodal, group-based exercise program, measures of postural stability (e.g., test of maximal standing balance range) improved compared with a control group (56). More recently, Krebs et al. (51) demonstrated that 6 mo of moderate exercise improves mediolateral stability.

The results of the present study extend our knowledge about the potential reversibility of gait instability to measures on the basis of the fluctuations of walking rhythm and features of gait that have previously been associated with fall risk (36, 40, 57). Age-associated changes in walking rhythm dynamics are apparently modifiable, at least in certain situations, and not necessarily an inevitable result of aging. A small, but significant, intervention effect was observed in the exercisers, and it appears that older adults with decreased physiological capacity were more responsive to the intervention. The randomized, placebo-controlled design suggests that the observed effects were due to the intervention and not merely to the "attention" received by the exercisers. We hypothesized that modification of the physiological mediators of gait instability would alter gait instability, and the results are consistent with this hypothesis. Nonetheless, the multimodal nature of the intervention and our finding that gait instability is significantly associated with multiple physiological and neuropsychological factors limit our ability to identify the specific mechanisms of action of the intervention. The ability of exercise to partially restore muscle strength and function in older adults has been well documented (26, 62). Although much remains unknown about the plasticity of the aged motor control system (23), previous studies also indicate that age-associated changes in human motor control and performance may be modifiable in response to exercise and training, independent of the effects on subspinal, peripheral function (4, 5, 15, 49, 74, 76). The present results are consistent with these findings; however, additional studies, perhaps combined with functional neuroimaging, are required to more clearly define the response of gait instability to exercise.

The present study also lends support to the idea that balance, specifically, "standing still" performance, may be less germane to the functional balance needed during gait (51). Our findings of an exercise effect on gait instability without a parallel effect on gait speed also support the idea that stability at a self-selected gait speed "may be more important to elders' well-being than simply walking faster" (51). Perhaps, we should shift the emphasis from simply improving gait speed to restoring gait stability.

Similar to previous studies that found more profound exercise effects on gait in persons with more impaired gait (46, 55), we observed that exercisers were more likely to successfully reduce their gait instability if they started with relatively increased locomotor impairment and greater instability. This difference may reflect a general ceiling effect and limits on the modifiability of the involved underlying physiological systems. Alternatively, this effect may simply be due to the relatively moderate nature of the intervention. As is common with home-based exercise trials, the home-based exercise program was apparently not fully successful at eliciting a sufficient physiological response to the intervention in all subjects. Perhaps the ceiling effect would have been removed with an exercise program that produced more robust changes on muscle function and physiological capacity. Additional studies are needed to address this question. Nonetheless, the present findings suggest that these gait instability measures may be useful in identifying older adults who may be among those with the greatest need to reduce gait instability and also are likely capable of reducing gait instability, even with only relatively modest effort.

This study has a number of limitations. *1*) Although all subjects underwent a physical examination by the study physician, a comprehensive neurological examination was not performed. It is possible that undetected neuropathology may have contributed to the observed gait instability. Perhaps future studies should use other diagnostic tools to more fully evaluate and account for each subject's neurological status and the response to exercise. *2*) Ankle muscle weakness has been associated with postural instability and fall risk (56, 88) and may contribute to gait instability; however, we did not measure muscle strength of the plantar- or dorsiflexors. *3*) Because the exercise intervention did not achieve marked improvement in muscle strength, we can only speculate about the effects of a more robust exercise intervention on gait instability. An exercise study in the laboratory setting where the strength of the intervention is more readily tailored to each individual and the "dose" is controlled more precisely may also enable further study of the potential reversibility and plasticity of gait instability and allow us to determine if and how gait instability may be modified, even in stronger individuals. *4*) The relatively small sample size may have affected the multivariate analyses and limited our ability to determine all the factors that are independently associated with gait instability. *5*) The intervention was designed to improve function. Perhaps an intervention that was targeted to specifically reduce gait instability would have had a greater impact.

Future work will also be helpful in determining the most appropriate exercises and the optimal levels for reducing gait instability in older adults. It will also be helpful to directly compare measures of gait instability on the basis of the fluctuations in the timing of the gait rhythm with those based on kinematics, balance platform-based measures of postural control, and dynamic balance (17, 51, 56, 91), to study further the factors that contribute to gait instability and the complex interactions between instability, physiological capacity, neuropsychological function, and other mediators of these properties, and to further clarify the mechanisms whereby neuropsychological function modifies gait instability. The findings of the present study highlight the multifactorial nature of gait instability and its potential reversibility, at least in certain populations. Gait instability may not be an irreversible by-product of aging. Rather, improvements in gait stability apparently may be achievable by way of physiological adaptation during targeted, multimodal exercise regimens. Apparently, enhancement of the proximate physiological mediators of gait instability may improve gait instability itself. In addition, it appears that when attempting to restore gait stability, we should focus on improving neuropsychological function as well as physiological capacity. Despite intensive prevention efforts, falls in the elderly remain a major public health problem (48). Perhaps, an approach that focuses on physiological and neuropsychological factors may be useful for gaining additional insight into the etiology of gait instability as well as for augmenting our ability to reduce gait stability and fall risk and their deleterious sequelae via targeted interventions.

We thank Drs. David M. Buchner, Ary L. Goldberger, James O. Judge, and C. K. Peng for valuable assistance and discussions and the subjects for their time and effort.

This work was supported in part by National Institutes of Health Grants P01-DK-42618, AG-11812, AG-4100, AG-08812, and P41-RR-13622, by the American Federation for Aging Research, Tufts Associated Health Plans, Inc. (Waltham, MA), by the Brookdale Foundation (New York, NY), by US Department of Agriculture Cooperative Agreement 58-1950-9-001, and by the American Physiological Society (APS). J. M. Hausdorff was also supported in part by the APS Arthur C. Guyton Award for Excellence in Integrative Physiology. Exercise equipment used for subject testing was donated by Keiser Sports Health Equipment (Fresno, CA).

The contents of this publication do not necessarily reflect the views or policies of the US Department of Agriculture, neither does mention of trade names, commercial products, or organizations imply endorsement by the US Government.

REFERENCES

1. **Alexander NB.** Postural control in older adults. *J Am Geriatr Soc* 42: 93–108, 1994.
2. **Alexander NB.** Gait disorders in older adults. *J Am Geriatr Soc* 44: 434–451, 1996.
3. **Bassey EJ, Fiatarone MA, O'Neill EF, Kelly M, Evans WJ, and Lipsitz LA.** Leg extensor power and functional performance in very old men and women. *Clin Sci (Colch)* 82: 321–327, 1992.
4. **Baylor A.** Plasticity and exercise effects on aging motor function. In: *Development of Posture and Gait Across the Lifetime*, edited by Woollacott MH and Shumway-Cook A. Columbia, SC: University of South Carolina Press, 1989, p. 176–201.
5. **Bickford P.** Aging and motor learning: a possible role for norepinephrine in cerebellar plasticity. *Rev Neurosci* 6: 35–46, 1995.
6. **Bittner V, Weiner DH, Yusuf S, Rogers WJ, McIntyre KM, Bangdiwala SI, Kronenberg MW, Kostis JB, Kohn RM, and Guillotte M.** Prediction of mortality and morbidity with a 6-min walk test in patients with left ventricular dysfunction. SOLVD Investigators. *JAMA* 270: 1702–1707, 1993.
7. **Blin O, Ferrandez AM, Pailhous J, and Serratrice G.** Dopa-sensitive and dopa-resistant gait parameters in Parkinson's disease. *J Neurol Sci* 103: 51–54, 1991.
8. **Blin O, Ferrandez AM, and Serratrice G.** Quantitative analysis of gait in Parkinson patients: increased variability of stride length. *J Neurol Sci* 98: 91–97, 1990.
9. **Borg G and Linderholm H.** Perceived exertion and pulse rate during graded exercise in various age groups. *Acta Med Scand* 1967: 194–206, 1967.
10. **Brown M, Sinacore DR, and Host HH.** The relationship of strength to function in the older adult. *J Gerontol A Biol Sci Med Sci* 50: 55–59, 1995.
11. **Buchner DM, Cress ME, de Lateur BJ, Esselman PC, Margherita AJ, Price R, and Wagner EH.** The effect of strength and endurance training on gait, balance, fall risk, and health services use in community-living older adults. *J Gerontol A Biol Sci Med Sci* 52: M218–M224, 1997.
12. **Buchner DM, Cress ME, Wagner EH, de Lateur BJ, Price R, and Abrass IB.** The Seattle FICSIT/MoveIt study: the effect of exercise on gait and balance in older adults. *J Am Geriatr Soc* 41: 321–325, 1993.
13. **Buchner DM, Hornbrook MC, Kutner NG, Tinetti ME, Ory MG, Mulrow CD, Schechtman KB, Gerety MB, Fiatarone MA, and Wolf SL.** Development of the common data base for the FICSIT trials. *J Am Geriatr Soc* 41: 297–308, 1993.
14. **Buchner DM, Larson EB, Wagner EH, Koepsell TD, and de Lateur BJ.** Evidence for a non-linear relationship between leg strength and gait speed. *Age Ageing* 25: 386–391, 1996.
15. **Butefisch CM, Davis BC, Wise SP, Sawaki L, Kopylev L, Classen J, and Cohen LG.** Mechanisms of use-dependent plasticity in the human motor cortex. *Proc Natl Acad Sci USA* 97: 3661–3665, 2000.
16. **Cahalin LP, Mathier MA, Semigran MJ, Dec GW, and DiSalvo TG.** The six-minute walk test predicts peak oxygen uptake and survival in patients with advanced heart failure. *Chest* 110: 325–332, 1996.
17. **Collins JJ and DeLuca CJ.** Open-loop and closed-loop control of posture: a random-walk analysis of center-of-pressure trajectories. *Exp Brain Res* 95: 308–318, 1993.
18. **Crosbie WJ, Nimmo MA, Banks MA, Brownlee MG, and Meldrum F.** Standing balance responses in two populations of elderly women: a pilot study. *Arch Phys Med Rehabil* 70: 751–754, 1989.
19. **Desrosiers J, Bravo G, Hebert R, and Dutil E.** Normative data for grip strength of elderly men and women. *Am J Occup Ther* 49: 637–644, 1995.
20. **Dorfman LJ and Bosley TM.** Age-related changes in peripheral and central nerve conduction in man. *Neurology* 29: 38–44, 1979.
21. **Duncan PW, Chandler J, Studenski S, Hughes M, and Prescott B.** How do physiological components of balance affect mobility in elderly men? *Arch Phys Med Rehabil* 74: 1343–1349, 1993.
22. **Duncan PW, Weiner DK, Chandler J, and Studenski S.** Functional reach: a new clinical measure of balance. *J Gerontol* 45: M192–M197, 1990.
23. **Enoka RM.** Neural adaptations with chronic physical activity. *J Biomech* 30: 447–455, 1997.
24. **Ferrucci L, Guralnik JM, Buchner D, Kasper J, Lamb SE, Simonsick EM, Corti MC, Bandeen-Roche K, and Fried LP.** Departures from linearity in the relationship between measures of muscular strength and physical performance of the lower extremities: the Women's Health and Aging Study. *J Gerontol A Biol Sci Med Sci* 52: M275–M285, 1997.
25. **Fiatarone MA, Marks EC, Ryan ND, Meredith CN, Lipsitz LA, and Evans WJ.** High-intensity strength training in nonagenarians. Effects on skeletal muscle. *JAMA* 263: 3029–3034, 1990.
26. **Fiatarone MA, O'Neill EF, Ryan ND, Clements KM, Solares GR, Nelson ME, Roberts SB, Kehayias JJ, Lipsitz LA, and Evans WJ.** Exercise training and nutritional supplementation for physical frailty in very elderly people. *N Engl J Med* 330: 1769–1775, 1994.
27. **Folstein MF, Folstein SE, and McHugh PR.** "Mini-mental state." A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res* 12: 189–198, 1975.
28. **Forette F, Seux ML, Thijs L, Le Divenah A, Perol MB, Rigaud AS, Latour F, Bouchacourt P, and Staessen JA.** Detection of cerebral aging, an absolute need: predictive value of cognitive status. *Eur Neurol* 39: 2–6, 1998.
29. **Gabell A and Nayak USL.** The effect of age on variability in gait. *J Gerontol* 39: 662–666, 1984.
30. **Giampaoli S, Ferrucci L, Cecchi F, Lo NC, Poce A, Dima F, Santaquilani A, Vescio MF, and Menotti A.** Hand-grip strength predicts incident disability in non-disabled older men. *Age Ageing* 28: 283–288, 1999.
31. **Grigsby J, Kaye K, Baxter J, Shetterly SM, and Hamman RF.** Executive cognitive abilities and functional status among community-dwelling older persons in the San Luis Valley Health and Aging Study. *J Am Geriatr Soc* 46: 590–596, 1998.
32. **Guralnik JM, Ferrucci L, Simonsick EM, Salive ME, and Wallace RB.** Lower-extremity function in persons over the age of 70 years as a predictor of subsequent disability. *N Engl J Med* 332: 556–561, 1995.
33. **Guralnik JM, Simonsick EM, Ferrucci L, Glynn RJ, Berkman LF, Blazer DG, Scherr PA, and Wallace RB.** A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. *J Gerontol* 49: M85–M94, 1994.
34. **Guyatt G, Sullivan M, Thompson P, Fallen EL, Pugsley SO, Taylor DW, and Berman LB.** The 6-minute walk: a new measure of exercise capacity in patients with chronic heart failure. *Can Med Assoc J* 132: 919–923, 1985.

35. **Hausdorff JM, Cudkowicz ME, Firtion R, Wei JY, and Goldberger AL.** Gait variability and basal ganglia disorders: stride-to-stride variations in gait cycle timing in Parkinson's and Huntington's disease. *Mov Disord* 13: 428–437, 1998.
36. **Hausdorff JM, Edelberg HE, Mitchell SL, Goldberger AL, and Wei JY.** Increased gait unsteadiness in community dwelling elderly fallers. *Arch Phys Med Rehabil* 78: 278–283, 1997.
37. **Hausdorff JM, Ladin Z, and Wei JY.** Footswitch system for measurement of the temporal parameters of gait. *J Biomech* 28: 347–351, 1995.
38. **Hausdorff JM, Lertratanakul A, Cudkowicz M, Peterson AL, and Goldberger AL.** Dynamic markers of altered gait rhythm in amyotrophic lateral sclerosis. *J Appl Physiol* 88: 2045–2053, 2000.
39. **Hausdorff JM, Mitchell SL, Firtion R, Peng C-K, Cudkowicz ME, Wei JY, and Goldberger AL.** Altered fractal dynamics of gait: reduced stride interval correlations with aging and Huntington's disease. *J Appl Physiol* 82: 262–269, 1997.
40. **Hausdorff JM, Rios D, and Edelberg HK.** Gait variability and fall risk in community living older adults: a one-year prospective study. *Arch Phys Med Rehabil.* In press.
41. **Hausdorff JM, Zemany L, Peng C-K, and Goldberger AL.** Maturation of gait dynamics: stride-to-stride variability and its temporal organization in children. *J Appl Physiol* 86: 1040–1047, 1999.
42. **Hu MH and Woollacott MH.** Multisensory training of standing balance in older adults. I. Postural stability and one-leg stance balance. *J Gerontol* 49: M52–M61, 1994.
43. **Jacqmin-Gadda H, Fabrigoule C, Commenges D, and Dartigues JF.** A 5-year longitudinal study of the Mini-Mental State Examination in normal aging. *Am J Epidemiol* 145: 498–506, 1997.
44. **Judge JO, King MB, Whipple R, Clive J, and Wolfson LI.** Dynamic balance in older persons: effects of reduced visual and proprioceptive input. *J Gerontol A Biol Sci Med Sci* 50: M263–M270, 1995.
45. **Judge JO, Schechtman K, and Cress E.** The relationship between physical performance measures and independence in instrumental activities of daily living. The FICSIT Group Frailty and Injury: Cooperative Studies of Intervention Trials. *J Am Geriatr Soc* 44: 1332–1341, 1996.
46. **Judge JO, Underwood M, and Gennosa T.** Exercise to improve gait velocity in older persons. *Arch Phys Med Rehabil* 74: 400–406, 1993.
47. **Kamen G, Sison SV, Duke Du CC, and Patten C.** Motor unit discharge behavior in older adults during maximal-effort contractions. *J Appl Physiol* 79: 1908–1913, 1995.
48. **Kannus P, Parkkari J, Koskinen S, Niemi S, Palvanen M, Jarvinen M, and Vuori I.** Fall-induced injuries and deaths among older adults. *JAMA* 281: 1895–1899, 1999.
49. **Karni A, Meyer G, Jezzard P, Adams MM, Turner R, and Ungerleider LG.** Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature* 377: 155–158, 1995.
50. **Katz SE, Ford AB, Moskowitz RW, Jackson BA, and Jaffe MW.** Studies of illness in the aged. The index of ADL: a standardized measure of biological and psychosocial function. *JAMA* 185: 914–919, 1963.
51. **Krebs DE, Jette AM, and Assmann SF.** Moderate exercise improves gait stability in disabled elders. *Arch Phys Med Rehabil* 79: 1489–1495, 1998.
52. **Langenfeld H, Schneider B, Grimm W, Beer M, Knoche M, Riegger G, and Kochsiek K.** The six-minute walk—an adequate exercise test for pacemaker patients? *Pacing Clin Electrophysiol* 13: 1761–1765, 1990.
53. **Lawton MP and Brody EM.** Assessment of older people: self-maintaining and instrumental activities of daily living. *Gerontologist* 9: 179–186, 1969.
54. **Lipkin D, Scriven A, Crake T, and Poole-Wilson P.** Six minute walking test for assessing exercise capacity in chronic heart failure. *Br Med J* 292: 653–655, 1986.
55. **Lord SR, Lloyd DG, Nirui M, Raymond J, Williams P, and Stewart RA.** The effect of exercise on gait patterns in older women: a randomized controlled trial. *J Gerontol A Biol Sci Med Sci* 51: M64–M70, 1996.
56. **Lord SR, Ward JA, and Williams P.** Exercise effect on dynamic stability in older women: a randomized controlled trial. *Arch Phys Med Rehabil* 77: 232–236, 1996.
57. **Maki BE.** Gait changes in older adults: predictors of falls or indicators of fear? *J Am Geriatr Soc* 45: 313–320, 1997.
58. **Miller RA, Thaut MH, McIntosh GC, and Rice RR.** Components of EMG symmetry and variability in Parkinsonian and healthy elderly gait. *Electroencephalogr Clin Neurophysiol* 101: 1–7, 1996.
59. **Morganti CM, Nelson ME, Fiatarone MA, Dallal GE, Economos CD, Crawford BM, and Evans WJ.** Strength improvements with 1 yr of progressive resistance training in older women. *Med Sci Sports Exerc* 27: 906–912, 1995.
60. **Mulrow CD, Gerety MB, Kanten D, Cornell JE, DeNino LA, Chiodo L, Aguilar C, O'Neil MB, Rosenberg J, and Solis RM.** A randomized trial of physical rehabilitation for very frail nursing home residents. *JAMA* 271: 519–524, 1994.
61. **Nakamura T, Meguro K, Yamazaki H, Okuzumi H, Tanaka A, Horikawa A, Yamaguchi K, Katsuyama N, Nakano M, Arai H, and Sasaki H.** Postural and gait disturbance correlated with decreased frontal cerebral blood flow in Alzheimer disease. *Alzheimer Dis Assoc Disord* 11: 132–139, 1997.
62. **Nelson ME, Fiatarone MA, Morganti CM, Trice I, Greenberg RA, and Evans WJ.** Effects of high-intensity strength training on multiple risk factors for osteoporotic fractures. A randomized controlled trial. *JAMA* 272: 1909–1914, 1994.
63. **Nelson ME, Layne JE, Nuerenberger A, Bernstein MA, Kaliton D, Judge J, Buchner D, and Fiatarone Singh MA.** The effects of a home-based exercise program on functional performance in the frail elderly: an update (Abstract). *Med Sci Sports Exerc* 31: 1929, 1999.
64. **Newell KM and Corcos DM.** *Variability and Motor Control*. Champaign, IL: Human Kinetics, 1993.
65. **Ostchega Y, Harris TB, Hirsch R, Parsons VL, Kington R, and Katzoff M.** Reliability and prevalence of physical performance examination assessing mobility and balance in older persons in the US: data from the Third National Health and Nutrition Examination Survey. *J Am Geriatr Soc* 48: 1136–1141, 2000.
66. **Penninx BW, Guralnik JM, Ferrucci L, Simonsick EM, Deeg DJ, and Wallace RB.** Depressive symptoms and physical decline in community-dwelling older persons. *JAMA* 279: 1720–1726, 1998.
67. **Penninx BW, Leveille S, Ferrucci L, van Eijk JT, and Guralnik JM.** Exploring the effect of depression on physical disability: longitudinal evidence from the established populations for epidemiologic studies of the elderly. *Am J Public Health* 89: 1346–1352, 1999.
68. **Phillips P.** Grip strength, mental performance and nutritional status as indicators of mortality risk among female geriatric patients. *Age Ageing* 15: 53–56, 1986.
69. **Potter JM, Evans AL, and Duncan G.** Gait speed and activities of daily living function in geriatric patients. *Arch Phys Med Rehabil* 76: 997–999, 1995.
70. **Potvin AR, Syndulko K, Tourtellotte WW, Lemmon JA, and Potvin JH.** Human neurologic function and the aging process. *J Am Geriatr Soc* 28: 1–9, 1980.
71. **Rantanen T, Guralnik JM, Foley D, Masaki K, Leveille S, Curb JD, and White L.** Midlife hand grip strength as a predictor of old age disability. *JAMA* 281: 558–560, 1999.
72. **Reuben DB, Siu AL, and Kimpau S.** The predictive validity of self-report and performance-based measures of function and health. *J Gerontol Med Sci* 47: M106–M110, 1999.
73. **Reuben DB and Siu AL.** An objective measure of physical function in elderly outpatients: the physical performance test. *J Am Geriatr Soc* 38: 1105–1112, 1990.
74. **Rikli RE and Edwards DJ.** Effects of a three-year exercise program on motor function and cognitive processing speed in older women. *Res Q Exerc Sport* 62: 61–67, 1991.
75. **Rossiter-Fornoff JE, Wolf SL, Wolfson LI, and Buchner DM.** A cross-sectional validation study of the FICSIT common data base static balance measures. Frailty and injuries: cooper-

ative studies of intervention techniques. *J Gerontol A Biol Sci Med Sci* 50: M291–M297, 1995.
76. **Sanes JN and Donoghue JP.** Plasticity and primary motor cortex. *Annu Rev Neurosci* 23: 393–415, 2000.
77. **Schultz AB.** Mobility impairment in the elderly: challenges for biomechanics research. *J Biomech* 25: 519–528, 1992.
78. **Seeman TE, Charpentier PA, Berkman LF, Tinetti ME, Guralnik JM, Albert M, Blazer D, and Rowe JW.** Predicting changes in physical performance in a high-functioning elderly cohort: MacArthur studies of successful aging. *J Gerontol* 49: M97–M108, 1994.
79. **Stewart AL, Hays RD, and Ware JE Jr.** The MOS short-form general health survey. Reliability and validity in a patient population. *Med Care* 26: 724–735, 1988.
80. **Tinetti ME, Mendes de Leon CF, Doucette JT, and Baker DI.** Fear of falling and fall-related efficacy in relationship to functioning among community-living elders. *J Gerontol* 49: M140–M147, 1994.
81. **Tinetti ME and Powell L.** Fear of falling and low self-efficacy: a case of dependence in elderly persons. *J Gerontol* 48: 35–38, 1993.
82. **Tinetti ME, Williams TF, and Mayewski R.** Fall risk index for elderly patients based on number of chronic disabilities. *Am J Med* 80: 429–434, 1986.
83. **Topp R, Mikesky A, Wigglesworth J, Holt W Jr, and Edwards JE.** The effect of a 12-week dynamic resistance strength training program on gait velocity and balance of older adults. *Gerontologist* 33: 501–506, 1993.
84. **Topper AK, Maki BE, and Holliday PJ.** Are activity-based assessments of balance and gait in the elderly predictive of risk of falling and/or type of fall? *J Am Geriatr Soc* 41: 479–487, 1993.
85. **Washburn RA, Smith KW, Jette AM, and Janney CA.** The Physical Activity Scale for the Elderly (PASE): development and evaluation. *J Clin Epidemiol* 46: 153–162, 1993.
86. **Weiner DK, Duncan PW, Chandler J, and Studenski SA.** Functional reach: a marker of physical frailty. *J Am Geriatr Soc* 40: 203–207, 1992.
87. **West BJ and Griffin L.** Allometric control of human gait. *Fractals* 6: 101–108, 1998.
88. **Whipple RH, Wolfson LI, and Amerman PM.** The relationship of knee and ankle weakness to falls in nursing home residents: an isokinetic study. *J Am Geriatr Soc* 35: 13–20, 1987.
89. **Winter DA and Yack HJ.** EMG profiles during normal human walking: stride-to-stride and intersubject variability. *Electroencephalogr Clin Neurophysiol* 67: 402–411, 1987.
90. **Wolfson L, Judge J, Whipple R, and King M.** Strength is a major factor in balance, gait, and the occurrence of falls. *J Gerontol A Biol Sci Med Sci* 50: 64–67, 1995.
91. **Wolfson L, Whipple R, Derby C, Judge J, King M, Amerman P, Schmidt J, and Myers D.** Balance and strength training in older adults: intervention gains and tai chi maintenance. *J Am Geriatr Soc* 44: 498–506, 1996.
92. **Wolfson L, Whipple R, Judge J, Amerman P, Derby C, and King M.** Training balance and strength in the elderly to improve function. *J Am Geriatr Soc* 41: 341–343, 1993.
93. **Yesavage JA, Brink TL, Rose TL, Lum O, Huang V, Adey M, and Leirer VO.** Development and validation of a geriatric depression screening scale: a preliminary report. *J Psychiatr Res* 17: 37–49, 1982.