Increased Walking Variability in Elderly Persons with Congestive Heart Failure

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OBJECTIVES: To determine the effects of congestive heart failure on a person’s ability to walk at a steady pace while ambulating at a self-determined rate.

SETTING: Beth Israel Hospital, Boston, a primary and tertiary teaching hospital, and a social activity center for elderly adults living in the community.

PARTICIPANTS: Eleven elderly subjects (aged 70–93 years) with well compensated congestive heart failure (NY Heart Association class I or II), seven elderly subjects (aged 70–79 years) without congestive heart failure, and 10 healthy young adult subjects (aged 20–30 years).

MEASUREMENTS: Subjects walked for 8 minutes on level ground at their own selected walking rate. Footswitches were used to measure the time between steps. Step rate (steps/minute) and step rate variability were calculated for the entire walking period, for 30 seconds during the first minute of the walk, for 30 seconds during the last minute of the walk, and for the 30-second period when each subject’s step rate variability was minimal. Group means and 95% confidence intervals were computed.

MAIN RESULTS: All measures of walking variability were significantly increased in the elderly subjects with congestive heart failure, intermediate in the elderly controls, and lowest in the young subjects. There was no overlap between the three groups using the minimal 30-second variability (elderly CHF vs elderly controls: P < 0.001, elderly controls vs young: P < 0.001), and no overlap between elderly subjects with and without congestive heart failure when using the overall variability. For all four measures, there was no overlap in any of the confidence intervals, and all group means were significantly different (P < 0.05).


Congestive heart failure alters walking in several ways. It significantly reduces habitual walking velocity and, because of fatigue or shortness of breath, it limits the time a person can walk without being forced to rest.

Changes in gait are likely related to reduced cardiac output, diminished oxygen ventilation, increased pulmonary capillary wedge pressure, reduced regional blood flow to skeletal muscle, and decreased skeletal muscle strength, all common sequelae of heart failure.

In fact, walking distance and velocity have been used as diagnostic measures for the assessment of congestive heart failure and have been found to correlate with traditional assessments of functional capacity, exercise tolerance, and degree of congestive heart failure.

Moreover, walking distance has also been reported to predict long-term morbidity and mortality in patients with heart failure.

In preliminary observations, we noted that congestive heart failure may also modify the dynamics of walking by limiting the ability to walk at a steady pace. Figure 1 shows an example of the walking step rate of an elderly subject with congestive heart failure. Shortness of breath forced this woman to rest several times during this walk. However, even when dyspnea did not preclude walking, her step rate appeared to be highly irregular and unsteady. We hypothesized that increased variability of step rate might be characteristic of patients with congestive heart failure. To test this hypothesis, we compared the variability of step rate in a group of elderly subjects with well compensated congestive heart failure with that of a group of elderly control subjects and a group of healthy young subjects.

METHODS

Subjects

Three groups of subjects were studied: elderly subjects with congestive heart failure, elderly control subjects (no congestive heart failure), and healthy, young subjects. Selection criteria included: independent ambulation (i.e., no assistive devices), independent living in the community, no overt neurological pathology, no acute illness, no restrictions in activities of daily living, and stable medications. Eighteen...
elderly subjects were divided into two groups, based on the presence of congestive heart failure. The Charlson index, a previously validated, weighted scale that takes into account number and seriousness of concomitant disease, was used to assess comorbidity in each elderly subject.12 The index increases with comorbidity (0 = no comorbidity). To isolate comorbidities separate from heart failure, the index was computed after excluding congestive heart failure. Ten healthy young men, mean age 26 years (range: 20–30 years), with no history of any neurological or cardiovascular disease, served as a second reference group. All subjects provided informed written consent.

Assessment of Gait

Subjects were instructed to walk at their self-determined, usual rate for 8 minutes without stopping (unless necessary). A self-determined pace was chosen because, at least in healthy subjects, walking variability is minimized at this rate.13 Subjects walked indoors around an obstacle free, circular path approximately 130 meters in length. To monitor gait, heelstrike was detected using ultra-thin, force-sensitive switches taped underneath each shoe.11 The data were recorded on an ambulatory recorder. Subsequently, the recorded gait signal was digitized, and the time between heelstrikes was automatically computed. An instantaneous step rate (steps per minute) time series was then produced by taking the reciprocal of the linearly interpolated time between heelstrikes sampled at 2 Hz as previously described.14 In some subjects, walking distance was also measured by an investigator who traced the subject’s path with a rolling tape measure.

Measurement of Walking Variability

Four measures of walking variability were calculated from each subject’s time series, each providing a slightly different perspective of walking variability. First, the overall step rate standard deviation was computed for the time series, excluding the first and last 30 seconds of walking and any portions in which the subject stopped or slowed significantly (defined as portions of the time series with instantaneous step rates less than 40 steps/minute). This measure reflects the overall variability of the entire time series. A second measure of variability was used to assess the ability of a subject to walk continuously over a shorter time period. The standard deviation of the walking rate during 30 seconds of walking was calculated at 15-second intervals over the entire walk, and the 30-second period with the lowest standard deviation was determined. The lowest or minimal variability was defined as the standard deviation during that 30-second period. This measure reflects ‘the best effort’ in terms of variability (ie, the least erratic gait). We also computed the standard deviation during the first minute of walking, starting from 30 seconds after the start of the walk for the next 30 seconds, and the last minute of walking, starting 1 minute before and ending 30 seconds before the end of the walk. For these last two measures, any portions with a step rate below 40 steps/minute were excluded. The corresponding step rate was also computed for each of these four variability measures.

Statistical Analysis

A boot-strapped based statistical procedure15,16 that is effective in analyzing small data sets was used to estimate 95% and 95% confidence intervals and to, thereby, provide upper and lower bounds on group mean estimates. In addition, the nonparametric Kruskal-Wallis test was used to test for statistical differences between groups. If this test showed significant differences among the groups, multiple Wilcoxon Rank Sum tests were performed to compare two groups at a time. The Wilcoxon Signed Rank test was used for within-group comparisons. These nonparametric, relatively conservative tests make no assumptions about the underlying distribution of the groups being compared. Statistical analysis was performed using SAS software (Cary, NC). Differences were considered statistically significant only if there was no overlap in the confidence limits and if $P < 0.05$. Results are reported as mean ± standard deviation.

RESULTS

Characteristics of the two elderly groups are shown in Table 1. Eleven of the elderly subjects had well compensated congestive heart failure, and seven elderly subjects did not have heart failure. Among the subjects with congestive heart failure, five were classified as NY Heart Association (NYHA) class I, and 6 as class II. The etiology of the heart failure was due to a variety of causes including hypertension, valvular disease, and coronary artery disease. All subjects had no history of alcoholic cardiomyopathy. Height and weight of the two elderly groups and the young subjects (young height: 1.8 ± 0.1 meters; weight: 72.2 ± 9.4 kg) were similar.

A summary of the four variability measures is presented in Table 2. All measures of walking variability were significantly increased in the elderly subjects with congestive heart failure, intermediate in the elderly controls, and lowest in the young subjects. Interestingly, there was no overlap among any individuals in the three groups using the minimal 30-second variability (elderly CHF vs elderly controls, $P < 0.001$; elderly controls vs young, $P < 0.001$) and no overlap between elderly subjects with and without congestive heart failure when using overall variability (elderly CHF vs elderly controls, $P < 0.001$) (see Figure 2). For all four measures, there was no overlap in any of the confidence intervals, and all group means were significantly different ($P < 0.05$). By all accounts, walking variability was significantly increased in the elderly subjects with congestive heart failure.
Table 1. Characteristics of the elderly subjects

<table>
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<tr>
<th></th>
<th>Subjects with CHF</th>
<th>Elderly Controls</th>
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<tbody>
<tr>
<td><strong>Height (meters)</strong></td>
<td>1.6 ± .1</td>
<td>1.6 ± .1</td>
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<tr>
<td><strong>Weight (Kg)</strong></td>
<td>65.1 ± 11.6</td>
<td>67.4 ± 12.0</td>
</tr>
<tr>
<td><strong>Age (yrs)</strong></td>
<td>81 ± 7</td>
<td>74 ± 3</td>
</tr>
<tr>
<td>(range: 70–93)</td>
<td>(range: 70–79)*</td>
<td></td>
</tr>
<tr>
<td><strong>Sex (women:men)</strong></td>
<td>7:4</td>
<td>5:2</td>
</tr>
<tr>
<td><strong>History of angina</strong></td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Valvular disease</strong></td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td><strong>Systemic hypertension</strong></td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td><strong>Chronic obstructive pulmonary disease</strong></td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Diabetes</strong></td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>History of CVA</strong></td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>History of cancer</strong></td>
<td>1 (breast cancer)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Charlson comorbidity index</strong></td>
<td>1 ± 1</td>
<td>0*</td>
</tr>
<tr>
<td><strong>Medications</strong></td>
<td></td>
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<tr>
<td>Angiotensin-converting enzyme inhibitors</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Beta-blockers</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Digoxin</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Diuretics</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Calcium antagonists</td>
<td>3</td>
<td>0</td>
</tr>
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</table>

*P < 0.05.

Examples of walking time series from the three groups are shown in Figure 3A. The increased step rate variability in the time series of this elderly subject with congestive heart failure can be readily observed during the entire walk. Note also that the elderly subject with congestive heart failure never achieves a steady walk comparable to that of the other two subjects over any 30-second period. Step rate histograms for these subjects are shown in Figure 3B. Consistent with the group differences illustrated in Figure 2, it is again apparent that the overall variability is largest in the elderly subject with congestive heart failure and smallest for the young subject.

A summary of the step rates corresponding to each of the four variability measures is presented in Table 3. Step rate tended to be lowest in the elderly subjects with congestive heart failure, intermediate in the elderly control subjects and highest in the young subjects. All measures of step rate were significantly different only when comparing the elderly subjects with congestive heart failure to the young subjects. However, step rate of elderly subjects with congestive heart failure was not significantly different from that of elderly controls, and there was considerable overlap between the two groups. As observed in Figure 4, step rate variability was independent of step rate: low step rate variability occurred both at relatively high and low step rates, and high variability occurred both at high and low step rates.

As was the case with step rate, there was significant overlap in total distance walked among the two elderly groups, and the group differences were not significant (P = NS). Elderly subjects with congestive heart failure walked 281 ± 82 meters (n = 7; range, 142–404), and elderly controls walked 386 ± 91 meters (n = 6; range, 279–555).

Distance walked was not measured in the young subjects. Distance walked was inversely related to overall walking variability (adjusted r² = -.5; P < 0.05) among the subjects for whom this data was available. Nevertheless, distance walked did not segregate the two elderly groups.

Excluding the last two columns of Tables 2 and 3, one notes that the variability and step rates during the first and last minutes were not identical within each group. The differences in variability were not significant within any group (note: the same result was obtained if the first and seconds halves of the walks were compared). Interestingly, however, there was a statistically significant increase in the step rate at the end of the walk compared with that at the beginning of the walk for the young subjects (increase = 2.2 steps/min; P < 0.05) and for the elderly subjects with congestive heart failure (increase = 7.3 steps/min; P < 0.05). In fact, step rate at the end of the walk was greater than that at the beginning in 10 of 11 elderly subjects with congestive heart failure.

The 30-second period with minimal step rate variability generally occurred about 3 minutes into the walk for all three groups. For the elderly subjects with congestive heart failure, minimal variability occurred at 3.0 ± 2.5 minutes into the walk. For the elderly controls, this occurred at 3.3 ± 2.8 minutes, and for young subjects, this occurred at 3.0 ± 1.6 minutes (P = NS). Therefore, time of minimal variability was not a distinguishing feature.

Among the elderly subjects with congestive heart failure, there was no significant dependence of any variability measure on comorbidity index or age. Both relatively low and high variability occurred in these subjects, independent of comorbidity and age. Linear regression analysis showed that the slopes relating each of the four variability measures to comorbidity index and age were not significantly different from zero, and the corresponding correlation coefficients were also not statistically significant (P = NS). For example, the Pearson correlation coefficient relating morbidity index to minimal variability was r = 0.07 (P = NS). Among the subjects in the elderly control group, there also was no significant positive dependence of any variability measure on comorbidity index or age. (The only significant relationship was a slight negative correlation between age and minimal variability, i.e., variability decreased with increasing age with a slope equal to -0.03 steps/min/year). When the two elderly groups were pooled together, there was a slight dependence of some variability measure on age (e.g., minimal variability = 0.19 steps/min/year × age = 11.4; adjusted r² = 0.4) and a small dependence of overall walking variability on comorbidity (adjusted r² = 0.2). The three other variability measures were not correlated with comorbidity index. Using multiple regression analysis, there was no dependence of any walking variability measure on comorbidity, but the small age dependence remained for two of the variability measures. Two subjects with congestive heart failure had significant "gaps," as described in Methods, in their walking time series. (These portions were not included in the calculation of walking variability). One of these subjects had three gaps and the other had one. All were due to dyspnea.

**DISCUSSION**

This study demonstrates for the first time that the ability to walk at a steady pace is significantly reduced in elderly subjects with congestive heart failure. All measures of walk-
Table 2. Walking variability (steps/min) group means*

<table>
<thead>
<tr>
<th></th>
<th>Minimal 30 Seconds</th>
<th>Overall</th>
<th>First Minute of Walk</th>
<th>Last Minute of Walk</th>
</tr>
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<tbody>
<tr>
<td>Old CHF</td>
<td>4.5 ± 1.8 (3.7-5.3)</td>
<td>9.0 ± 3.9 (7.4-11)</td>
<td>7.3 ± 4.2 (5.5-11.8)</td>
<td>9.3 ± 5.4 (6.9-12.0)</td>
</tr>
<tr>
<td>Old</td>
<td>2.0 ± 0.1 (1.9-2.1)</td>
<td>4.1 ± 0.7 (3.7-4.5)</td>
<td>3.7 ± 0.8 (3.2-4.2)</td>
<td>3.4 ± 0.9 (2.9-4.0)</td>
</tr>
<tr>
<td>Young</td>
<td>1.3 ± 0.2 (1.2-1.4)</td>
<td>3.0 ± 0.6 (2.8-3.2)</td>
<td>2.5 ± 1.1 (2.0-3.0)</td>
<td>2.3 ± 1.0 (1.8-2.8)</td>
</tr>
</tbody>
</table>

*For each measure of variability there was a statistically significant difference between (1) elderly subjects with congestive heart failure (CHF) and elderly controls, (2) elderly subjects with congestive heart failure and young subjects, and (3) elderly controls and young subjects. Numbers in parentheses here and in Table 3 are the 5 and 95% confidence intervals of the mean.

Walking variability were significantly increased in elderly subjects with congestive heart failure in comparison with elderly controls and young subjects. These differences were not simply step rate dependent; several subjects with congestive heart failure walked with relatively high step rates (and increased variability), while some young subjects walked at relatively low rates (but with low variability). Furthermore, although step rate tended to decrease in subjects with mild congestive heart failure, the decrease was not significant compared to the step rate of elderly controls. Thus, our finding of increased walking variability in elderly persons with heart failure is apparently independent of changes in step rate.

Diagnosis of congestive heart failure, particularly milder degrees, may be difficult. The 6-minute walk, a test in which a subject is instructed to cover as much ground as possible in 6 minutes, has been applied to address this problem. Studies using this test demonstrated that distance covered is a reliable measure for distinguishing patients with severe congestive heart failure (NYHA class III), but it is somewhat less effective in assessing patients with milder heart failure. Consistent with these results, we found that step rate and distance walked tended to decrease in subjects with mild heart failure; however, these measures did not discriminate heart failure subjects from the elderly controls. In contrast, two measures of walking variability were successful at completely distinguishing all elderly subjects with heart failure from all elderly controls.

Further study will determine whether in fact these variability measures could be used to augment the diagnostic capabilities of walking tests for subjects with mild heart failure.

Is the increase in walking variability among elderly subjects with congestive heart failure simply the result of fatigue from an 8-minute walk? Four observations suggest that this explanation does not account for our findings: (1) Overall walking variability, a measure that takes into account the steadiness of the entire walk, was increased in all subjects with congestive heart failure. (2) Step rate of subjects with congestive heart failure was significantly larger near the end of the walk compared with the beginning, a result not consistent with fatigue effects. (3) At no time during the walk were elderly subjects with congestive heart failure able to achieve step-to-step stability (ie, low variability) at a level comparable to that of the other subjects. (4) Even during the first minute of this walk at a self-determined pace, when fatigue effects are likely to be small, walking variability was significantly increased in the elderly subjects with congestive heart failure. Therefore, it is unlikely that the observed increase in walking variability was simply due to the fatigue of the walk. Rather, it appears that step-to-step stability is diminished in elderly subjects with congestive heart failure independent of any long-term fatigue that might result from an 8-minute walk.

What might cause the increased walking variability in elderly subjects with congestive heart failure? The time between heelstrikes (ie, step rate) can be viewed as the output of a complex, multidimensional neuromuscular control system that integrates afferent and efferent components. In the absence of pathology, these systems are coordinated to produce remarkably stable locomotor patterns. However, damage to any component may affect output stability. For example, unsteadiness in gait is increased in elderly fallers, in those with senile dementia, and in those with parkinsonism. Proposed mechanisms for the increased gait variability in these populations include failure of the automatic, gait-patterning mechanisms, damage to integrating pathways, and increased variability of muscle force production. Like elderly fallers, patients with congestive heart failure have decreased muscle strength, poor endurance, and reduced cardiopulmonary reserve. These factors apparently contribute to the decreased walking distance and velocity observed during walking tests and might also affect gait stability.

This study has several limitations. The young subjects were all men, while the elderly groups were a mixture of men...
Figure 3. A. Examples of the step rate time series obtained from an elderly subject with compensated congestive heart failure (NYHA class I, age 84), an elderly subject without congestive heart failure (age 75), and a 30-year-old healthy subject. B. Histograms of
the time series illustrate how much more variable the instantaneous step rate of the elderly subject with congestive heart failure was in
comparison to the others. Normalized step rate is defined as the instantaneous step rate minus the mean step rate. For example, if
instantaneous step rate ranged from 80 to 120 per minute and the mean step rate was 100 per minute, normalized step rate would
range from -20 to 20 per minute. To compare these three subjects with the results presented in Table 2 and Figure 2, note that overall
variability was 2.4, 4.5, and 5.9 steps/minute, and minimal variability was 1.5, 2.1, and 3.7 steps/minute in the young, elderly, and
elderly subject with congestive heart failure, respectively.

and women. However, since the proportion of men and
women in the two elderly groups was similar, and since there
were no apparent gender differences, it is unlikely that the
increase in walking variability in the subjects with congestive
heart failure was attributable to effects of gender. Another
limitation is that the two elderly groups were not perfectly
matched with regard to medication use.

Two other factors might have contributed to the
increase in walking variability in the subjects with congestive
heart failure. This group was slightly older and had
increased comorbidity compared with the elderly control
group. While it is likely that age and comorbidity have
some impact on walking variability, certain findings indi-
cate that these potentially confounding factors are not
solely responsible for the increase in walking variability:
(1) Among the elderly subjects with congestive heart
failure, there was no significant dependence of any
variability measure on comorbidity index or age. (2) Among
the elderly control subjects, the only dependence of any
variability measure on comorbidity and age was a small
decrease in minimal variability with age. Thus, for all
practical purposes, there was essentially no dependence of
any variability measure on age or comorbidity index in
this group as well. (3) Among all elderly subjects, walking
variability did not depend on comorbidity when control-
ling for age. (4) Among all elderly subjects, there was some
dependence of walking variability on age, but only in two
of the four variability measures. Furthermore, this depen-
dence was quite small. (5) For every subject with conges-
tive heart failure, overall variability and minimal variabil-
ity were both larger than in all other subjects. This
occurred despite significant overlap among the two elderly
groups in both age and comorbidity. Thus, the finding of
increased walking variability in elderly persons with con-
gestive heart failure apparently is independent of comor-
bidity. While age probably plays some role, it is unlikely

<table>
<thead>
<tr>
<th>Table 3. Step rate (steps/min) group means*</th>
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<tr>
<td>Minimum 30 Seconds</td>
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<tr>
<td>-------------------</td>
</tr>
<tr>
<td>Old CHF</td>
</tr>
<tr>
<td>Old</td>
</tr>
<tr>
<td>Young</td>
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*For each step rate measure, the only significant difference was between elderly subjects with congestive heart failure (CHF) and young subjects.
**Denotes a within-group significant difference between the step rate during the first and last minutes (detected using a pairwise statistic).
that the small age difference between the two elderly groups was responsible for the almost twofold increase in all measures of walking variability.

Further investigation is needed to clarify the mechanism(s) responsible for the observed increase in step rate variability in elderly subjects with congestive heart failure. It will also be interesting to determine if step rate variability can be used to extend the diagnostic capabilities of the measures already provided by the 6-minute walk. In addition, it will be informative to study walking variability in young subjects with congestive heart failure and to examine more fully the interactions between comorbidity, age, congestive heart failure, and walking variability. Results of the present investigation demonstrate that congestive heart failure in older persons is associated with not only with changes in walking time and velocity, but also with increased step-to-step variability.

ACKNOWLEDGMENTS

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REFERENCES


