METHODS

A New Technique for Simultaneous Monitoring of Electrocardiogram and Walking Cadence

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A new technique for simultaneously recording continuous electrocardiographic (ECG) data and walking step rate (cadence) is described. The ECG and gait signals are recorded on 2 channels of an ambulatory Holter monitor. Footfall is detected using ultrathin, force-sensitive foot switches and is frequency modulated. The footfall signal provides an indication of the subject's activity (walking or standing), as well as the instantaneous walking rate. Twenty-three young and elderly subjects were studied to demonstrate the use of this ECG and gait recorder. High-quality gait signals were obtained in all subjects, and the effects of walking on the electrocardiogram were assessed. Initial investigation revealed the following findings: (1) Although walking rates were similar in young and elderly subjects, the elderly had both decreased heart rate (HR) variability ($p < 0.005$) and increased cadence variability ($p < 0.0001$). (2) Overall, there was an inverse relation between HR and cadence variability ($r = -0.73$). Three elderly subjects with no known cardiac disease had HR and cadence variability similar to those of the young, whereas elderly subjects with history of congestive heart failure were among those with the lowest HR variability and the highest cadence variability. (3) Low-frequency ($\cong 0.1$ Hz) HR oscillations (frequently observed during standing) persisted during walking in all young subjects. (4) In some subjects, both step rate and HR oscillated at the same low frequency ($\cong 0.1$ Hz) previously identified with autonomic control of the baroreflex. The modified Holter monitor enabled enhanced evaluation of the relation between the electrocardiogram and walking; it should augment assessment of conventional ECG measures, because changes in HR, ischemia, arrhythmias and HR variability can now be correlated with physical activity. (Am J Cardiol 1992;70:1064–1071)

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We describe a new technique for simultaneously recording continuous walking rate and the electrocardiogram (ECG). Using a modified Holter monitor and ultrathin, force-sensitive foot switches, we can quantitatively relate beat-to-beat changes in the ECG to physical activity. This augments assessment of conventional electrocardiographic measures, because changes in heart rate (HR), ischemia, rhythm and HR variability can be correlated with physical activity. To demonstrate the use of the modified Holter monitor and its ability to augment interpretation of changes in the ECG, we studied 23 young and elderly subjects during periods of supine rest and walking and assessed the effects of walking on the ECG.

Simultaneous recording of the ECG and footfall also provides a unique means for assessing beat-to-beat changes in HR. HR variability has been studied widely, because it provides a noninvasive window into autonomic nervous system function and because reduced HR variability has been associated with congestive heart failure, coronary artery disease, aging and mortality in patients after myocardial infarction.[1–7] The modified Holter facilitates correlation of HR variability with gait dynamics and physical activity, thus providing further insight into HR variability, autonomic nervous system function and pathology. Assessment of the relation between variations in HR and step rate (cadence) was performed in 23 subjects to show how the modified Holter monitor may be used to study functional conditions and the related effects of age, disease and cadence variability on HR dynamics.

METHODS

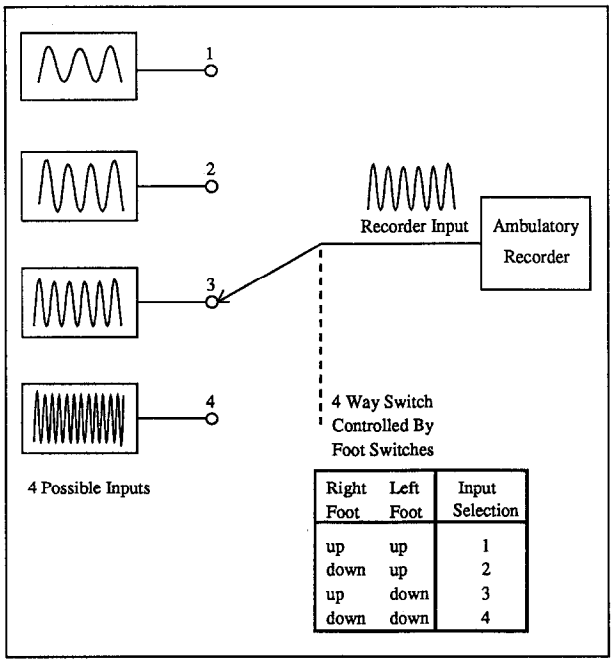
Electrocardiogram and walking cadence monitoring: The ECG and cadence are recorded simultaneously and continuously on a 2-channel ambulatory recorder (model 455b, Del Mar Avionics, Irvine, California). Footfall is detected using ultrathin (<0.05 inch), force-sensitive switches (part 154, Interlink Electronics, Carpinteria, California) taped underneath each shoe. When the foot makes contact with the ground and applies force to the switch, the switch is activated. When the foot leaves the ground during the swing phase of gait, the switch is turned off. The on-off pattern provides an indication of a subject's activity (e.g., walking or standing), as well as the rate at which it is performed.

The recorder we use has 2 channels, 1 of which is used for the ECG. To record the activity of both feet (2 signals) on the other channel, the footfall signal is connected to a small, battery-powered interface circuit that produces the signal for recording. This interface takes as input the 2 foot switches (4 combinations of on-off states), and using frequency modulation, it generates a sine wave at 1 of 4 frequencies, depending on the state

of the foot switches (Figure 1). This method enables us to establish unique states for supine resting, standing and walking. A detailed schematic of the circuit is available from the authors.

The recorded signals are played back on a Del Mar Avionics Electrocardioscanner (model 655) and digitized at 416 Hz/channel. After playback, the footfall signal is decoded by determining which of the 4 sine-wave frequencies is present at any given time. Because the correspondence between frequency and foot switch state is known (Figure 1), determination of the frequency establishes the state of each foot switch. The original on-off footfall pattern then reemerges (Figure 2). The footfall signal is automatically analyzed by a computer program that marks the beginning of each step by locating the time the decoded footfall signal goes from off to on (Figure 2). Each beat of the ECG is also identified and classified (annotated) using an automated arrhythmia detector.[8] Computer results are reviewed manually and edited as necessary. HR and cadence (steps/min) are then calculated by taking the reciprocal of the RR interval and step duration. Evenly sampled, instantaneous HR and cadence were obtained for spectral analysis by resampling the interbeat and interstep intervals at 2 Hz.

Subjects: Twenty-three subjects were recruited to participate in this pilot study. Subjects were divided into young and elderly groups. All subjects were living independently in the community and participating in normal activities of daily living. Selection criteria included no



Right Foot	Left Foot	Input Selection
up	up	1
down	up	2
up	down	3
down	down	4

FIGURE 1. Functional block diagram showing how foot switches control input to recorder. Four frequencies are used to differentiate between standing (both switches on), standing on right foot only (right foot switch on), standing on left foot only (left foot switch on), and supine (no foot support, and neither switch is on). Voltage-controlled oscillator with 2 binary inputs encodes 4 combinations of 2 on-off switch states as 4 distinct frequencies and acts as 4-way switch.

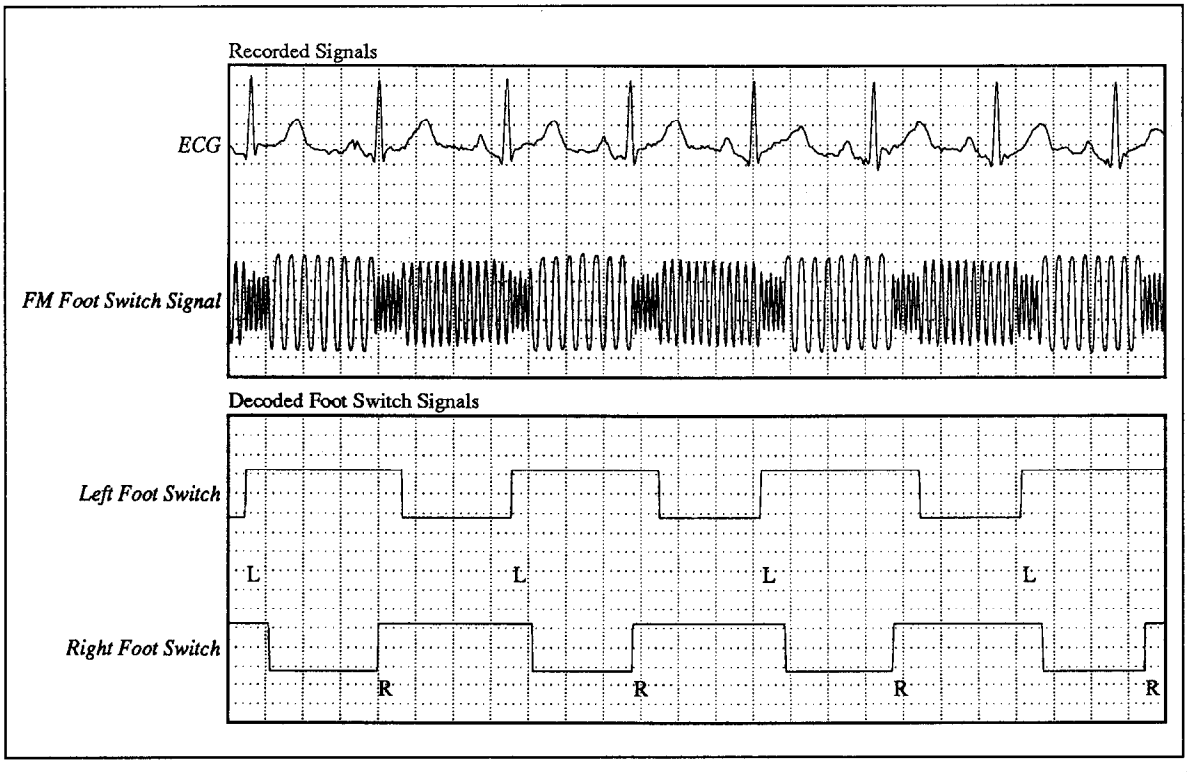


FIGURE 2. Electrocardiogram (ECG) and footfall signals during 5 seconds of walking after playback and digitization *(top)* and after decoding *(bottom)*. Three frequencies can be observed in frequency-modulated (FM) signal corresponding to 3 different foot switch states. Fourth frequency, which occurs when neither switch is activated, is not seen during this walking sequence because 1 foot was always in contact with ground. When foot switch is activated during stance, decoded signal goes from low to high, as seen in decoded foot switch signals. *Annotations* corresponding to beginning of right and left foot stance are displayed and marked with Rs and Ls, respectively. Each frequency corresponds to different combination of on-off foot switch states.

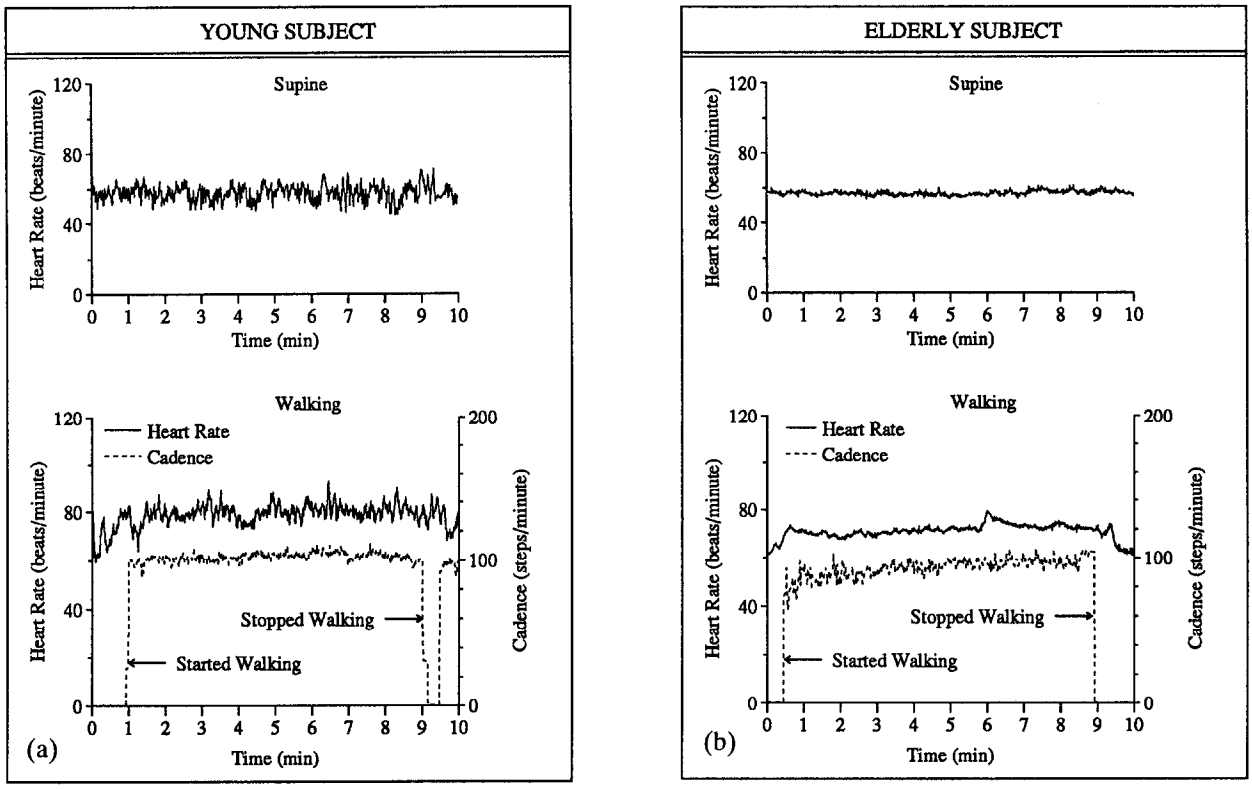


FIGURE 3. Heart rate and cadence time series for young *(a)* and elderly *(b)* subjects.

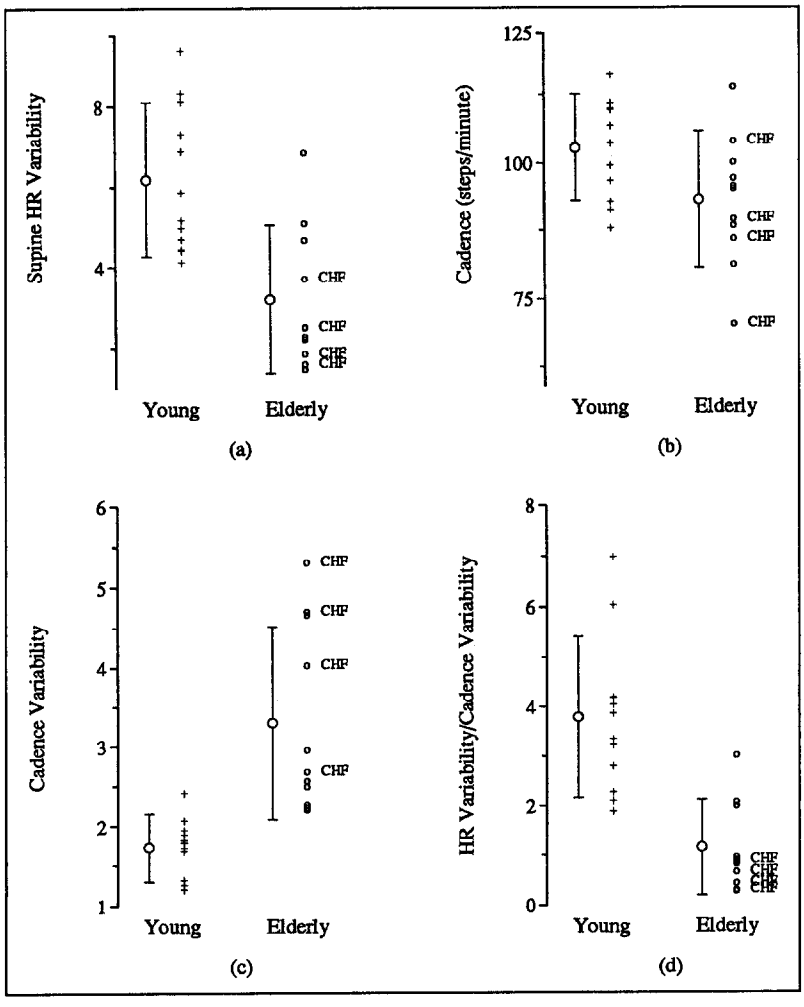


FIGURE 4. Variability of heart rate (HR) and cadence in young and elderly subjects. *(a)* HR variability in young and elderly subjects during supine rest (young 6.2 ± 1.8% and elderly 3.2 ± 1.7%; p <0.005). *(b)* Cadence in young and elderly subjects (young 103 ± 9 steps/min and elderly 93 ± 12 steps/min; p >0.05). *(c)* Cadence variability in young and elderly subjects (young 1.7 ± 0.4% and elderly 3.3 ± 1.2%; p <0.0001). *(d)* Ratio of supine HR to cadence variability in young and elderly subjects (young 3.8 ± 1.5 and elderly 1.2 ± 0.9; p <0.0005). *Errors bars* correspond to mean ± SD. *Plus signs* denote young adults; *circles* denote elderly adults with no history of congestive heart failure or coronary artery disease; *circles and CHF* denote elderly adults with history of congestive heart failure.

acute illness, sinus rhythm during supine rest, stable medications and the ability to ambulate independently. All subjects provided informed consent and medical histories. Mean age of the young subjects (2 women and 10 men) was 27 ± 5 years, and that of the elderly ones (7 women and 4 men) was 76 ± 5 years. Four elderly subjects had history of congestive heart failure (New York Heart Association functional class I or II); 2 also had history of coronary artery disease. Two elderly subjects were receiving calcium antagonists and 2 were receiving β blockers. Young subjects were not receiving any medications and had no history of any cardiovascular or gait-related disorder.

Experimental protocol: Subjects refrained from eating for ≥1 hour before the study, and testing was performed ≥2 hours after intake of medications. Subjects rested in the supine position for 21 minutes, stood in place for 6 minutes, and then walked for 8 minutes. Subjects were instructed to walk continuously at a normal, comfortable pace. All subjects wore their own walking shoes or sneakers (high heels were not worn).

Electrocardiogram and cadence analysis: Electrocardiographic data were analyzed during the last 5 minutes of supine rest (after 16 minutes of rest) and for the 5-minute period after 2 minutes of walking. During these periods, the mean HR and the HR coefficient of variation (100 × SD/mean) were calculated for subjects with <5% of ectopic beats. We also computed the frequency spectrum of HR and cadence to examine the relation between beat-to-beat changes in HR and cadence. The spectrum was computed using conventional, autoregressive, maximal entropy estimation techniques with a 12-pole model.[9] Spectral analysis has been used similarly to examine the relation between respiration, blood pressure and HR; peaks at similar locations in the spectra reflect an interaction between instantaneous regulation of HR, respiration and blood pressure.[10–13]

The cadence coefficient of variation during 1 minute of walking was calculated every 15 seconds during 8 minutes of walking. To ensure that comparable degrees of steady state were being compared, results during the 1-minute periods with the lowest cadence coefficient of variation were used for comparisons (defined as cadence variability). Furthermore, the ratio of HR variability to cadence variability was calculated for each subject to quantify the relation between these 2 indexes of variability and to obtain an overall measure of variability.

Results are reported as mean ± SD. The Wilcoxon rank sum test was used to test for differences between the young and elderly groups, and the Wilcoxon signed rank test was used to test for intragroup differences between the supine and walking experimental phases. These are nonparametric tests requiring no assumptions concerning the underlying distribution of the 2 groups. Statistical analysis was performed using SAS software programs (Cary, North Carolina). Statistical significance was defined as $p \leq 0.05$. Standard linear regression was also performed using SAS software.

RESULTS

A high-quality footfall signal was obtained in all 23 subjects. Typical time series of cadence and HR are shown in Figure 3. Step-to-step changes in cadence produce a time series similar to the instantaneous HR time series. Note the increase in HR at the beginning of walking in Figure 3a. The elderly subject shown had less HR variability than did the young one (especially at rest), whereas the young one had less variability of cadence during walking. Other differences between supine and walking states, and the interaction between the ECG and cadence are summarized in the following 3 sections.

Electrocardiographic changes during walking: In the supine position, young and elderly subjects had a similar mean HR (young 66 ± 9 beats/min, and elderly 72 ± 13 beats/min; $p > 0.05$). Rhythm was predominately sinus (>95% of beats) for all young and elderly subjects, and there was no sustained ectopy. During walking, HR increased significantly in both groups (young 22 ± 6 beats/min [$p < 0.002$]; and elderly 19 ± 7 beats/min [$p < 0.002$]), such that walking HR for the 2 groups was similar (young 89 ± 7 beats/min; and elderly 90 ± 13 beats/min [$p > 0.05$]). Because the quality of the electrocardiographic recording was inadequate for 2 young and 1 elderly subject, mean HRs are reported for 10 young and 10 elderly subjects. In general, there was no significant increase in ST depression or ectopy during walking. However, in 1 elderly subject, the frequency of ectopic beats markedly increased from 4.5 to 8.0%. In a second elderly subject, the HR rhythmicity changed dramatically from supine rest to walking. In that subject, normal sinus rhythm produced a flat time series with no fluctuations during supine rest (as in Figure 3b), but during walking, a wandering atrial pacemaker rhythm produced a HR time series with pronounced variability, with fluctuations like that normally seen in the young (e.g., Figure 3a).

Young subjects had significantly more HR variability during resting (young 6.2 ± 1.8% and elderly 3.2 ± 1.7%; $p < 0.005$) and walking (young 5.0 ± 1.4% and elderly 2.3 ± 0.5%; $p < 0.005$). For both groups, there was a slight reduction in HR variability in going from supine to walking (young −1.3 ± 2.2% and elderly −0.8 ± 1.4%), but this was not statistically significant in either group. Analysis of HR coefficient of variation during walking was not performed in the elderly subject with >5% ectopic beats, in the one with wandering atrial pacemaker or in those with inadequate electrocardiographic quality. Although elderly subjects generally had less HR variability than did young adults, variability in 3 elderly ones was within the range of the young (Figure 4a).

Cadence and cadence variability: Mean cadence (steps/min) for young subjects was slightly larger than that for elderly ones (young 103 ± 9 steps/min and elderly 93 ± 12 steps/min; $p > 0.05$), but there was considerable overlap between the groups (Figure 4b). Although cadence was similar, cadence variability was significantly larger in elderly subjects (young 1.7 ± 0.4% and elderly 3.3 ± 1.2%; $p < 0.0001$) (Figure 4c). Cadence variability of elderly subjects appeared to fall into 2 groups. One group had slightly more variability than the young subjects, and the second one had more than twice that of the young. Three of 4 subjects in the group

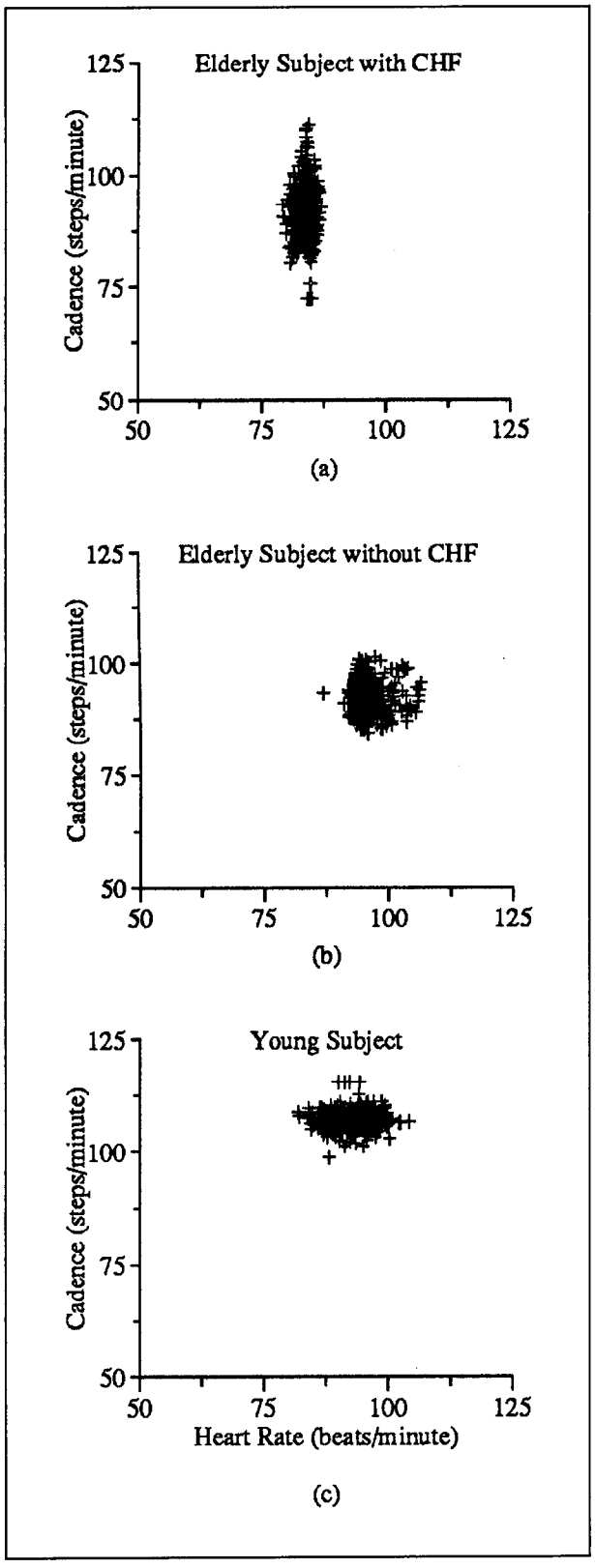


FIGURE 5. Cadence and heart rate (HR) during walking. *(a)* Elderly subject with history of coronary artery disease and congestive heart failure (CHF), *(b)* elderly subject with no history of cardiac disease, and *(c)* young subject. In subject with congestive heart failure *(a)*, there is little change in HR despite wide variations in cadence, but in healthy elderly subject *(b)* and young adult *(c)*, HR fluctuates widely, whereas there is less step rate variability.

with increased cadence variability had history of cardiac disease. In contrast, elderly subjects with greater HR variability (like young ones) also had cadence variability like the young.

Associations between heart rate and cadence: The ratio of HR variability to cadence variability was significantly larger in young subjects (Figure 4d), using both supine (young 3.8 ± 1.5 and elderly 1.2 ± 0.9; $p < 0.0005$) and walking (young 2.9 ± 1.0 and elderly 0.8 ± 0.4; $p < 0.0005$) HR variability. Elderly subjects with ratios >2 (more like the young than the other elderly) were the same 3 who had increased HR variability (Figure 4a) and reduced cadence variability (Figure 4c). In contrast, subjects with cardiac disease and several other elderly had a much lower ratio of HR to cadence variability. The differences in cadence and HR variability among the elderly are further shown in Figure 5. Some elderly subjects had no HR variability during walking (Figure 5a), whereas their cadence fluctuated widely; others (Figure 5b) had moderate amounts of HR variability and low cadence variability, as seen in the young (Figure 5c).

There were some subjects in whom the small-scale beat-to-beat and step-to-step changes in HR and cadence were clearly related. Figure 6 shows 1 example. For this elderly subject, HR and cadence were both periodic at approximately the same fundamental frequency (0.06 Hz). Results of a young subject who had similar periodicity in HR and cadence are shown in Figure 7a. Similar peaks were observed in the spectrum at approximately the same frequency (0.06 to 0.1 Hz) in other subjects; however, in some cases, the peaks occurred only in HR (Figure 7b), and in others, it occurred only in cadence (Figure 7c). Whereas there were peaks in the HR power spectrum in this frequency band (0.06 to 0.1 Hz) in all young and several elderly subjects, there was no consistent difference between young and old with regard to co-occurrence of the spectral peaks.

There was an inverse, exponential relation between HR and cadence variability across all subjects (supine HR vs cadence variability: $r = -0.73$, $p < 0.0001$; walking HR vs cadence variability: $r = -0.65$, $p < 0.005$). High HR variability was usually coupled with low cadence variability, and low HR variability was most often observed with high cadence variability (Figure 8). There was overlap between young and old subjects, but the young generally had high HR and low cadence variability. Elderly subjects (especially those with history of cardiac disease) tended to have low HR and high cadence variability. However, there were some elderly subjects with high HR and low cadence variability, like the young. Thus, even within the elderly group, the inverse relation between variability of HR and cadence persisted ($r = -0.53$).

DISCUSSION

Using a modified ambulatory monitor, we demonstrated a new means to evaluate the relation between the ECG and gait. The concurrent recording of ECG and cadence enabled assessment of interactions between ECG and walking, and proved useful in several respects.

We showed activity-related changes in HR, rhythm and HR variability that would probably be useful in determining disease/therapy characteristics, as well as idiosyncratic medication effects. In this study, we used a 2-channel Holter recorder and recorded the footfall signal on the second channel. In practice, walking cadence can be recorded on the third channel of a 3-channel Holter recorder, enabling complete 2-channel assessment and diagnosis of ischemic electrocardiographic changes, as well as footfall information. The results suggest that with only modest expense, the modified ambulatory monitor is a useful means to noninvasively assess cardiovascular and gait function.

Previous studies showed that normal aging blunts HR variability[1-4,14,15] and that HR variability is also reduced in patients with congestive heart failure,[5,16] coronary artery disease[7] and diabetes.[6] Other studies have also found associations between increased gait variability and nervous system pathology[17-19] and falling,[18,20,21] whereas the direct effect of aging on gait variability is controversial.[21-23] The present study is unique in measuring both of these parameters in the same subjects. We found an inverse relation between HR and cadence variability. In several elderly subjects, high HR variability typical of young adults was present, but in others, HR variability was severely reduced. Reduced HR variability was probably a corollary of "normal" aging in some subjects, whereas in others, this was likely due to the cumulative effects of cardiac disease and aging. All subjects with reduced HR variability also had the highest cadence variability and the lowest ratio of HR to cadence variability. This suggests that certain consequences of aging or pathology may affect both control of HR and gait.

Other observations on the interactions between HR and walking cadence imply that there may be a direct

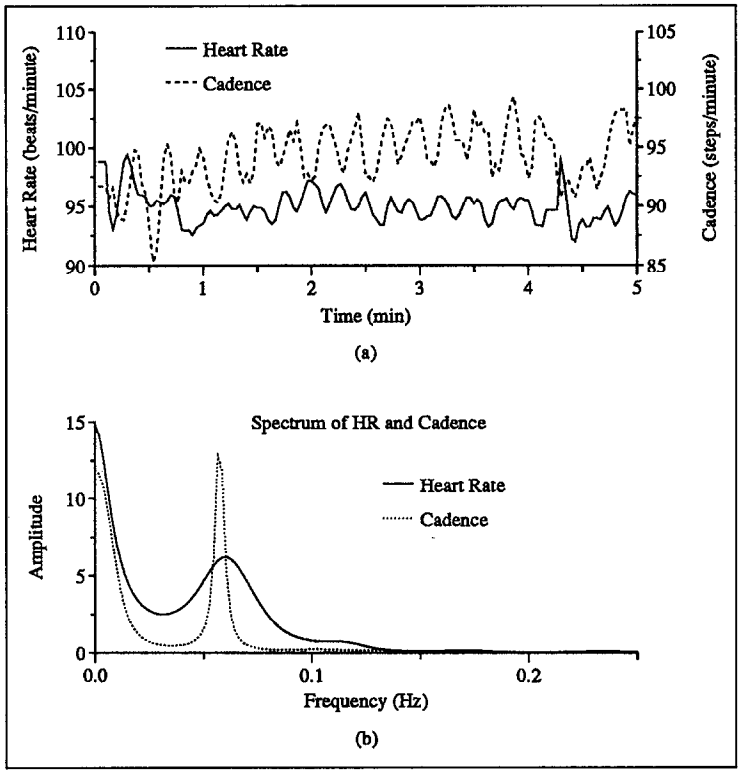


FIGURE 6. Correlation of heart rate (HR) and cadence during steady state walking. For this subject, beat-to-beat and step-to-step changes in HR and cadence were both periodic at approximately 0.06 Hz, as seen in *(a)* and elucidated in *(b)*. Results are presented for a 71-year-old woman with no significant medical history. Time series and spectral analysis of HR during supine rest and standing also revealed similar periodicity at 0.06 Hz.

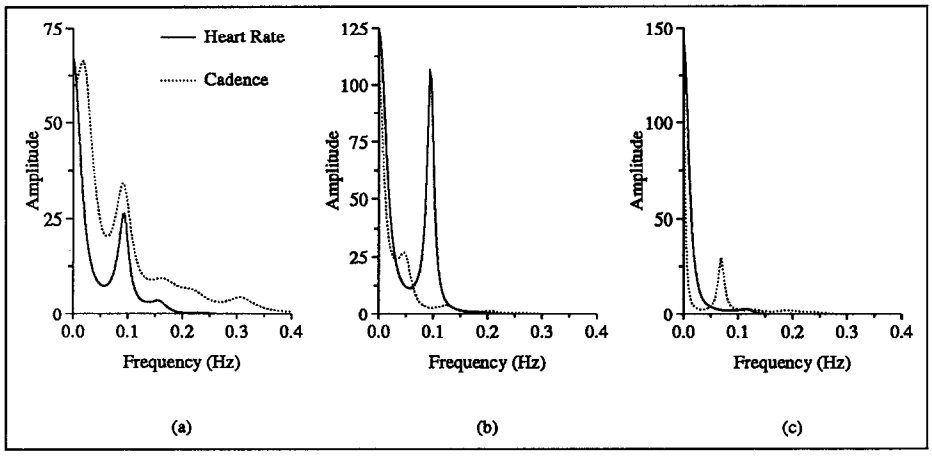


FIGURE 7. Spectral analysis of heart rate and cadence during walking. Spectrum in *(a)* and *(b)* are from young subjects, and *(c)* is from elderly one. Amplitude is presented in arbitrary units. See text for explanation.

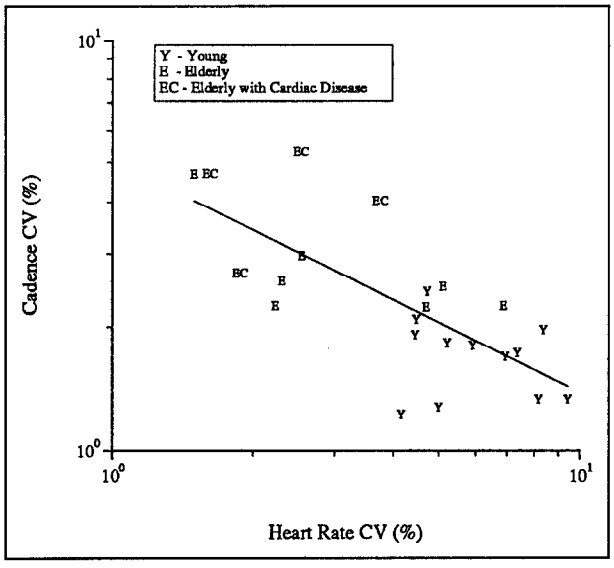


FIGURE 8. Cadence variability (CV) as function of heart rate variability. Inverse relation between cadence and supine heart rate variability was exponential with correlation coefficient of −0.73 ($p < 0.0001$).

relation between the physiologic control mechanisms of HR and gait. In several subjects, there were significant similarities in the periodicity of the beat-to-beat changes in HR and cadence. It is unclear what caused these ≅17-second cycles in HR and cadence, and if HR and cadence were directly related or entrained by another physiologic phenomenon (e.g., respiration or blood pressure), but it is unlikely that this was due to voluntary control of walking rate. These coincident fluctuations that were also evident in HR during standing occurred at approximately the same frequency as the Mayer-like waves[7,12,13] and may therefore represent the response of the baroreceptor. In some subjects, these fluctuations occurred only in HR or cadence, but not in both. Age did not account for the differences among subjects, and both the reason for between-subject differences and the underlying cause remains unclear. However, the marked similarities of beat-to-beat changes in HR and cadence suggest interaction in the control of HR and gait, which perhaps is of neurologic origin. Although walking is primarily under voluntary control and HR is under autonomic control, some control mechanisms of HR and gait may be related.

During maximal exercise, HR variability diminishes.[24,25] Therefore, one may have expected to see a significant reduction in HR variability during walking. Although HR variability decreased, it did not reach statistical significance in either young or elderly subjects, despite the large increase in HR in both groups. This absence of significance may be a result of a type II error. However, in 3 young and 5 elderly subjects, HR variability increased slightly during walking (e.g., Figure 3a), suggesting that this absence of significance is not only a result of the number of subjects. Most likely, HR variability did not decrease significantly during walking because subjects were not exercising maximally.

Preliminary observations raise the possibility that instantaneous control of HR and gait are related. However, our findings are limited by the small number of subjects, the varying degrees of health among the elderly, our reliance on self report for patient histories, and the differences in the numbers of men and women in the young and elderly groups. Additional investigation is also necessary to further clarify the effects of aging, congestive heart failure, coronary artery disease and other pathology and medications on the inverse relation between HR and cadence variability, as well as the similarities in beat-to-beat changes in HR and cadence. Concurrent measurement of respiration and blood pressure may elucidate the cause of the similarities in beat-to-beat cadence and HR changes. Despite these limitations, there appears to be a significant dynamic interaction between the ECG and walking rate, which can best be captured by recording ECG and walking cadence simultaneously. With this ability, the modified Holter recorder should improve the assessment capabilities of Holter monitoring and enrich our understanding of cardiovascular regulation and the relation between changes in the ECG and walking.

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