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Spectral characteristics of aging postural control

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Abstract

The purpose of this study was to apply techniques of spectral analysis to the study of postural control and determine if aging results in changes to spectral parameters obtained from postural forces. Subjects were young adults and elderly who live independently and had no difficulty performing tasks of daily living. Ground reaction forces were obtained from a measurement platform during repeated trials of static standing. Forces were analyzed using spectral analysis and selected parameters (central tendency and dispersion) were extracted from averaged spectral data. Significant differences were observed between age groups in all parameters extracted from spectra obtained from medial-lateral postural forces. Similar results were not obtained for data in the anterior-posterior direction. Results suggest that aging affects the spectral characteristics of postural forces used to maintain stability in the m-l direction.

Keywords: Posture, spectral analysis; Medial-lateral postural forces; Anterior-posterior postural forces; Falling; Aging

1. Introduction

Fall-related injuries represent a major threat to functional ability and quality of life of the elderly [1]. The incidence of falls increases with age, and in any given year approximately one-third of individuals aged 65 and older experience a fall [2]. Although most falls do not result in mortality, nearly 32% of all deaths resulting from fall-related injuries occur in individuals 85 years and older [3]. It is widely accepted that most falls are the result of both extrinsic and intrinsic factors [4,5] and are not caused by any single factor, rather they are often the result of several factors which occur simultaneously [6]. Age-related declines in physiological functioning result in slowness in executing the rapid adjustments necessary to maintain stability following minor perturbations to balance that commonly occur when an individual is engaged in activities of daily living [7,8]. This often results in individuals who can function adequately in the more restricted home environment, but who have difficulty maneuvering in unfamiliar situations where unpredictable and unexpected perturbations to postural stability may occur [9].

The belief that some impairments to the human motor system can be detected prior to the observation of clinical signs and that rehabilitation or slowing of a functional loss can be facilitated by early detection has stimulated interest in establishing 'biomarkers' of diminished motor control [10]. An initial step in implementing interventions to reduce falls is to identify measures that are sensitive to age-related changes that occur in postural control.

Postural adjustments underlying the maintenance of equilibrium are a result of the interaction between sensory and motor systems, which ultimately produce postural forces that result in movement of the center of pressure to maintain balance or posture. A variety of techniques have been used for clinical assessment of

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stability; these include measurement of selected gait parameters [4,7,11,12], sensory capacity [13,14], physiologic functioning [15–17] and measurement of postural forces [18–21]. Movement of the center of pressure (COP) and the variability of the movement of the center of pressure are traditional measures of stability. These measures, obtained from a measurement platform, are usually monitored for a period of time during quiet standing or following a controlled perturbation [22]. This research has been extensively reviewed by others [23,24]. Numerous studies have demonstrated that selected measures of postural sway, mean and variability of sway, increase in the elderly and may be indicative of declines in postural control [25–28]. Attempts to use these measures to identify elderly individuals 'at risk' of falling, however, have met with limited success [22,29,30].

Traditional time-dependent measures of postural control may not take into account the dynamic properties of the postural control system. For example, Newell et al. [31] reported data on postural control of adults diagnosed as developmentally disabled (profoundly and severely mentally retarded). Subjects were asked to stand on a measurement platform and perform selected postural tasks. The authors questioned whether traditional measures of center of pressure such as mean and variability, were good markers of stability. They concluded that such measures may in fact be inappropriate for describing more complex aspects of the stability of the postural control system. The authors reasoned that a simple measure of variability of movement of the center of pressure did not address the complexity of the system being examined.

Age-related declines in neurological and physiological systems have been implicated in the reduced postural control commonly exhibited in the elderly. It's possible that non-traditional methods of data analysis may provide an insight into impaired physiological functioning. For example, Lipsitz and Goldberger [32] suggested that periodicity exhibited by a physiological system may be an important marker of its functional ability. They describe robust systems as displaying a broader pattern of rhythmical behavior while impaired functioning may be characterized by a less variable periodicity. Glass and Mackey [33] similarly suggested that altered periodicity may be an indicator of reduced functional ability. They demonstrated that variations of rhythmical activity outside of 'normal' limits or the emergence of new rhythmical patterns where none previously existed were often markers of impaired ability [34]. A traditional approach to analyzing periodicity of a system is spectral analysis. Results of this analysis provide a distribution of energy of the signal in the frequency domain, rather than distributions of amplitude and time.

The purpose of this study was to apply spectral analysis to the study of postural control and determine if aging results in changes in selected spectral parameters. The long-term goal of this research is to determine whether changes in spectral characteristics of the postural control system, if they exist, can provide a 'clinical marker' of impaired stability.

2. Methods

2.1. Subjects

Subjects for the study were young adults (n = 30; age range 22–30 years; mean = 24.5 years) enrolled in upper division undergraduate courses in the Department of Exercise Science and elderly (n = 36; age range 66–86 years; mean 74.9 years) recruited from the local community. Gender was equally represented among young adults while females made up a higher percentage of the elderly group (10 males, 26 females). Prior to participation, elderly subjects were screened for pathology and/or medications that would influence postural stability. Subjects exhibiting conditions that would bias the results were not included in the subject pool. Measures used to characterize elderly subjects included general health status, perception of physical activity and clinical tests of postural stability. Results of this assessment are summarized in Table 1. Thirty-five percent of elderly subjects (n = 12) reported experiencing a fall in the past year. Of these subjects, incidence of falls during this period ranged from 1 to 6.

2.2. Experimental protocol

Participants came to the laboratory on three occasions at 1-week intervals during which data were collected from five trials (26.5 s) of static standing. A total of 15 trials were analyzed for each subject. Subjects were directed to stand quietly, with the arms at the sides and the eyes focused on a target placed at eye level, 6 feet in front. A black surround was used to focus the subject's attention and reduce distractions. Subjects were seated and provided sufficient rest between trials.

All data were collected without shoes; foot placement was standardized between trials. Prior to data collection a marker was placed on the medial border of the subject's feet at a point 2/3 the length of the foot measured from the heel. Subjects were asked to place these marks on a horizontal line at the center of the measurement platform. Medial borders of the feet were placed on two lines designed to externally rotate the feet 10 degrees. A trial was repeated if the subject lost balance during data collection.

2.3. Instrumentation

Horizontal forces were obtained in the medial lateral (m-l) and anterior-posterior (a-p) directions from a measurement platform mounted flush with the laboratory floor and related amplifiers (Kistler Instrument, Amherst NY, 9281B & 9861A). Shear forces were used

Table 1
Characteristics of elderly subjects

Measure	Mean (S.D.)	
General characteristics		
Age (years)	75.1 (5.0)	
Height (cm)	163.6 (8.1)	
Weight (kg)	69.7 (16.9)	
Pulse rate		
Standing	73.1 (12.2)	
Supine	67.6 (10.1)	
Blood pressure		
Standing	144.7 (25.3)/81.4 (9.6)	
Supine	144.5 (25.4)/81.4 (8.2)	
Health/activity perception		
Overall health perception[a]		
Current	3.1 (0.7)	
Compared to last year	2.2 (0.5)	
Doctor visits past year	4.7 (7.6)	
Days missed normal activity	12.2 (23.9)	
Exercise perception[b]		
Current (compared to others)	3.6 (1.0)	
Compared to last year	2.7 (0.8)	
Physical activity (hours/week)		
Light	22.1 (8.9)	
Moderate	4.1 (7.0)	
Vigorous	1.1 (2.6)	
Clinical stability measures[c]		
	Eyes open	Eyes closed
Normal stand	30.0 (0.0)	29.3 (3.0)
Semi-tandem stand	26.0 (9.0)	21.5 (11.0)
Tandem stand	17.0 (12.4)	5.5 (7.2)
Single leg stand (dominant)	10.1 (10.5)	1.6 (2.1)
Single leg stand (non-dominant)	7.0 (9.4)	1.3 (1.6)
	Time	No. steps
Preferred walk (10 ft)	3.7 (1.2)	6.2 (1.5)
Maximum walk (10 ft)	2.7 (0.8)	5.6 (2.0)

[a]Scale: 4, excellent–1, poor.
[b]Scale: 5, much more–1, much less.
[c]30 s maximum.

because they depict the accelerations of the center of mass. These accelerations represent the vibrations of the body while standing. Vibrational analysis has been traditionally used in the field of engineering to monitor mechanical systems for the diagnosis of impending impairment [35]. Analog output of the amplifiers was input (20 Hz) to a laboratory computer through a 12 bit A/D converter (Data Translation, Marlboro, MA, DT2801-A). Software was written (ASYST, Kiethley-Metrabyte, Taunton, MA) to collect and analyze data.

2.4. Statistical analysis

A Fast Fourier Transform (FFT) was used to estimate the frequency composition of the forces and calculate the power spectra (bandwidth 0.039–10 Hz, resolution = 0.039 Hz). Power spectra were averaged for individual subjects resulting in a spectral signature that characterized postural control for that individual.

Dependent variables were extracted from each subject's spectral signature (0.039–5 Hz) and used to characterize the changes in the composition of the force data associated with age (Table 1). Variables extracted included measures of central tendency: mean spectral frequency, f_{mean} (centroidal frequency); median spectral frequency, f_{median} (50% power frequency); and mode spectral frequency, f_{mode} (dominant frequency). Measures of spectral dispersion were also examined: frequency dispersion, f_{sd} (variability of the spectral data) and slope, s (slope of a regression line calculated on a double-log axis plot of the power spectrum). Spectral parameters selected for analysis were independent of measures traditionally used to normalize postural data.

Therefore, no attempt was made to normalize the data to limit of stability, leg length, foot length or height prior to analysis. The steps in this analysis are depicted in Fig. 1 and formulae used to calculate dependent variables are summarized in Table 2.

Spectral measures extracted from the spectral signatures were grouped by direction (m-l and a-p) and analyzed using two one-way MANOVAs with multiple dependent measures. Where appropriate the analyses were followed up by univariate ANOVAs ($P < 0.05$).

3. Results

Within-subject reliability of force data was determined using the root mean square amplitude (RMS) from each trial. Data were grouped by subject type and direction and analyzed using a subject by trial ANOVA. Results of this analysis indicated that there were no significant differences; intra-class reliability (R) measures of the RMS values were calculated (young adult, $R_{\text{m-l}} = 0.98$, $R_{\text{a-p}} = 0.99$; elderly, $R_{\text{m-l}} = 0.93$, $R_{\text{a-p}} = 0.97$)

Results of the MANOVAs indicated significant age effects for the spectral measures extracted from forces in both the m-l and a-p directions (m-l $F = 3.728$, $P = 0.0021$; a-p $F = 7.740$, $P = 0.0001$). Univariate ANOVAs were used to identify which spectral measures were significantly different.

3.1. Spectral measures of central tendency

Measures of central tendency (f_{mean}, f_{median}, and f_{mode}) were calculated for the power spectra. Mean frequency was defined as the centroid of the spectrum; median frequency represents the frequency at which 50% of the power contained in the spectral data is above and below; mode frequency is the dominant frequency of the spectrum. Results of this analysis are shown in Fig. 2. Significant age effects were found for each measure of central tendency in the m-l direction (f_{mean} $F = 9.68$, $P = 0.0028$; f_{median} $F = 9.99$, $P = 0.0024$; f_{mode} $F = 12.67$, $P = 0.0007$) but not the a-p direction.

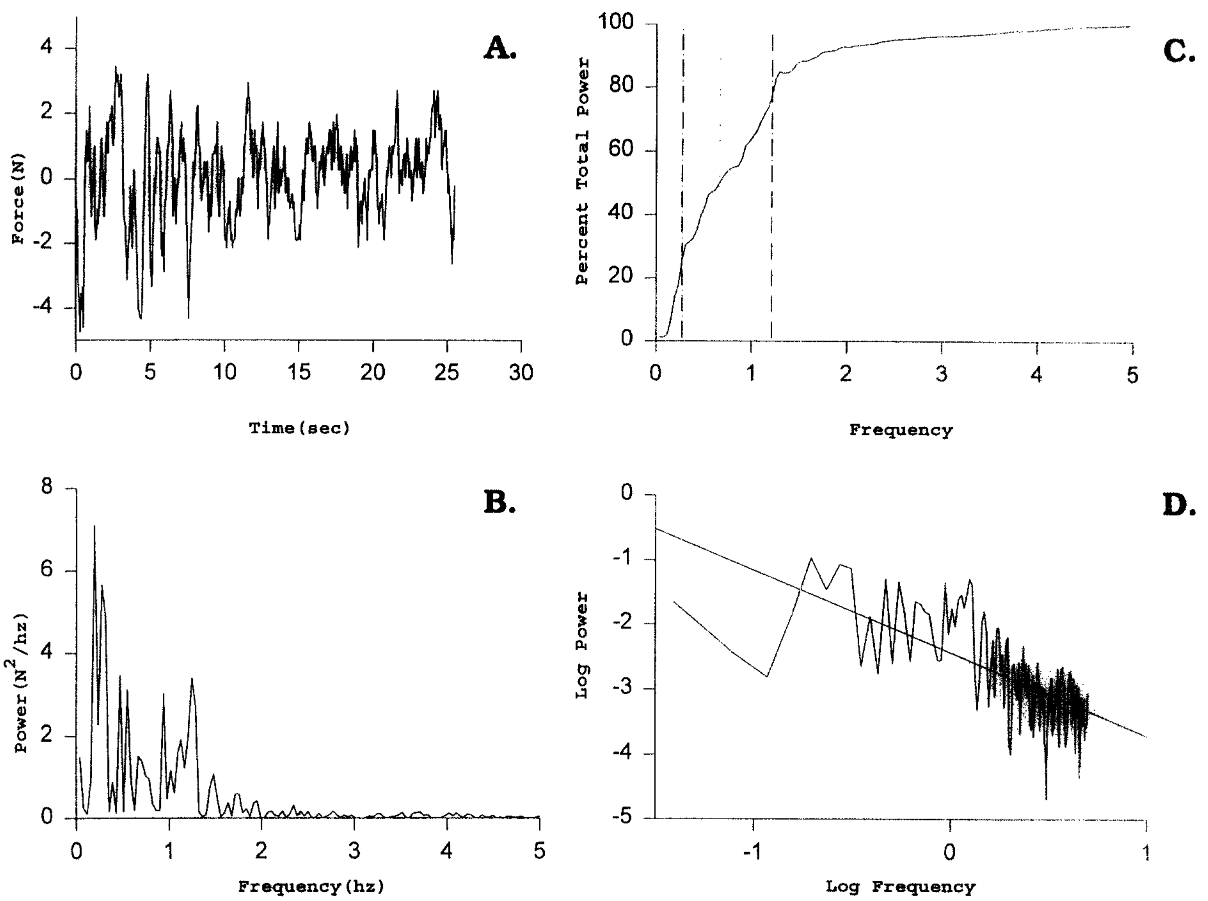

Fig. 1. Steps in analyzing spectral complexity of postural forces. (A) Collection of analog forces (m-l and a-p) were used to calculate RMS. (B) Frequency analysis (FFT) resulting in the power spectrum. Trial spectra were averaged resulting in spectral signatures (m-l and a-p) for each subject. Parameters extracted from the spectral signature included f_{mean}, f_{mode} and f_{sd}. (C) Spectral signatures were integrated and 50% total power was used to identify f_{median}. (D) Spectral signatures were graphically represented on a double-log axes plot and a regression line fitted to the data. Slope (s) of this line was used to characterize the distribution of energy of the spectra.

Table 2
Formulae used to extract dependent measures from force and spectral data

Symbol	Description	Unit of measure
T	Trial interval (26.5 s)	Sec
N	Number of elements in force vector (512)	Count
F_k	Force vector (m-l, a-p)	N
f_k	Frequency ($f_k = K/T$ $K = 0$, $N/2$)	Hz
S_k	Power spectrum	N^2/hz
RMS	Root mean square	N
f_{mean}	Centroid frequency	Hz
f_{median}	50% Power frequency	Hz
f_{mode}	Peak frequency	Hz
f_{sd}	Frequency dispersion	Hz
s	Slope	—

$$RMS = \sqrt{\frac{1}{N}\sum_{k=0}^{N-1} F_k^2} = \sqrt{\frac{1}{T}\sum_{k=0}^{N/2} S_k}$$

$$f_{sd} = \sqrt{\frac{\sum_{k=1}^{N/2} (f_k - f_{mean})^2 S_k}{\sum_{k=1}^{N/2} S_k}}$$

$$f_k = k/T \qquad k = 0, N/2$$

$$f_{mean} = \frac{\sum_{k=1}^{N/2} f_k s_k}{\sum_{k=1}^{N/2} S_k}$$

$$S = \frac{\left(\frac{N}{2}+1\right)\sum_{k=1}^{N/2} (\log S_k \log f_k) - \sum_{k=1}^{N/2} \log f_k \sum_{k=1}^{N/2} \log S_k}{\left(\frac{N}{2}+1\right)\sum_{k=1}^{N/2} \log^2 f_k - \left(\sum_{k=1}^{N/2} \log f_k\right)^2}$$

$$f_{median} = f_n \text{ where } P_n \le \frac{1}{2} < P_{n+1}$$

$$P_k = \frac{\frac{1}{T}\sum_{n=0}^{k} S_k}{RMS^2}$$

$$f_{mode} = f_{kmax} \text{ where } S_k \ge S_{kmax}$$

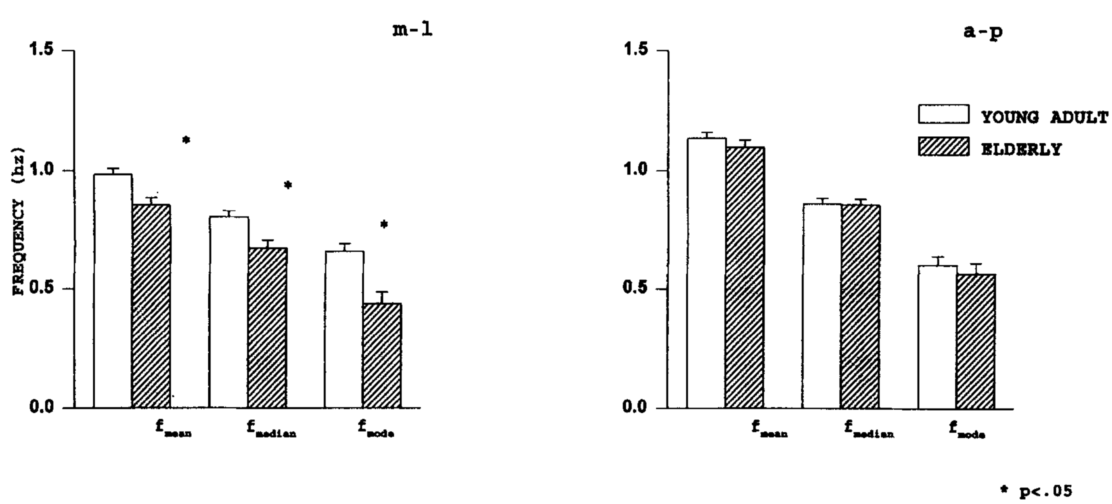

Fig. 2. Measures of central tendency of the spectra.

3.2. Distribution of spectral energy

Measures designed to quantify the distribution of energy of the power spectra included frequency dispersion (f_{sd}) and the slope (s) of a regression line of a double-log axes plot of the spectra (Fig. 3).

Variability of the power spectra was determined using a measure of frequency dispersion. This measure is similar in concept to that of a standard deviation and represents the distribution of spectral energy around f_{mean}. Elderly subjects exhibited significantly greater frequency dispersion than young adults in the m-l direction (f_{sd} $F = 13.19$, $P = 0.0006$). No difference in f_{sd} was observed in the a-p direction.

The slope of the regression line was calculated from a double-log axes plot (log amplitude vs. log frequency) of the spectral data. Results indicated that there was a significant age difference in the slopes of the spectral data calculated from forces in both the m-l (s $F = 5.42$, $P = 0.0231$) and a-p directions (s $F = 5.49$, $P = 0.0222$). Elderly subjects had a significantly more negative slope suggesting a greater distribution of spectral power concentrated at lower frequencies.

4. Discussion

The aim of this study was to determine if there are age related changes in the spectral characteristics of postural forces that may contribute to the decline in stability exhibited by the elderly. Forces were initially analyzed for within subject stability using inter-trial reliability of RMS measures. Inter-trial stability is important if changes in derived measures of postural control are to be used to quantify postural control and provide an insight into age-related changes. High inter-trial reliability of RMS values obtained in this study suggest that individuals exhibit a consistent pattern of postural forces to maintain static stability. Similar results have been found in previous investigations when measures derived from postural forces or displacement of the center of pressure were compared [16,36–40]. Although these studies used different measures and varied the period of time between test intervals, results indicate that individuals use a relatively consistent pattern of postural control during static standing.

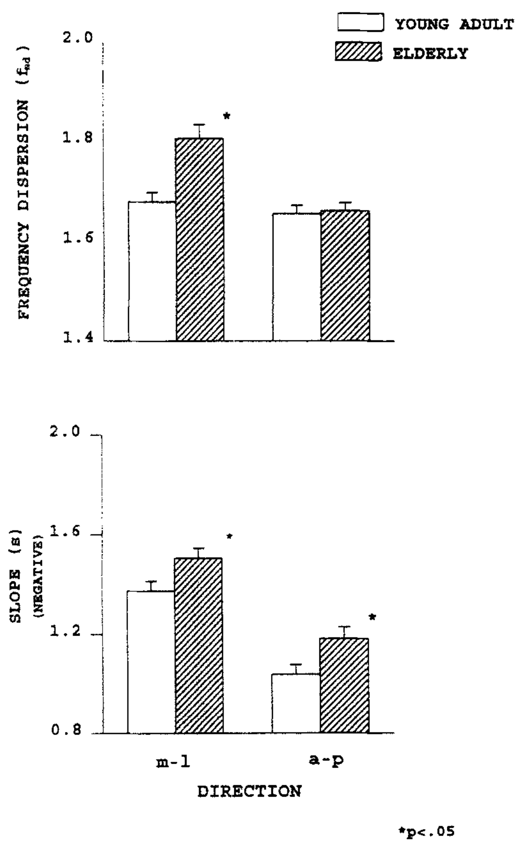

Fig. 3. Measures of energy dispersion of the spectra.

Frequency analysis and the resulting power spectrum, has been suggested as a useful technique to analyze time series data associated with dynamical systems [41]. Spectral analysis has been used previously to describe the characteristics of various physiological systems including the postural control system [42–44,46–48]. This investigation focused on age-related changes in the spectral characteristics of postural forces used to maintain static stability.

Central tendency parameters extracted from the spectral signature were significantly different for young adults and elderly in the m-l direction. Maki et al. [49,50] found similar results in a study designed to evaluate the relationship between postural control and falls. Elderly subjects were followed for a 1-year-period; during this time a total of 120 falls were reported by 37 subjects. Changes in selected measures of m-l postural control were found to be the best predictors of individuals at risk of falling. Mean frequency of sway during spontaneous standing was significantly lower in the m-l direction in subjects who fell.

Measures of the distribution of spectral energy support the premise that changes in parameters associated with m-l stability may be important contributors to age-related declines in postural stability. Power dispersion (m-l direction only) and slope were significantly different for elderly and young adults. These results indicate that there were age-related changes in the distribution of energy in the spectra generated from postural forces. These changes may be attributed to a shift in the distribution of energy of the spectra and/or the emergence of increased power at selected frequencies. Two descriptive techniques were used to characterize the changes observed in the spectra.

Spectral envelopes (m-l and a-p) were created by averaging subjects' spectral signatures (Fig. 4). Elderly subjects exhibited greater absolute power across all frequencies in both m-l and a-p forces than young adults. Spectral data collected on individual trials were nor-

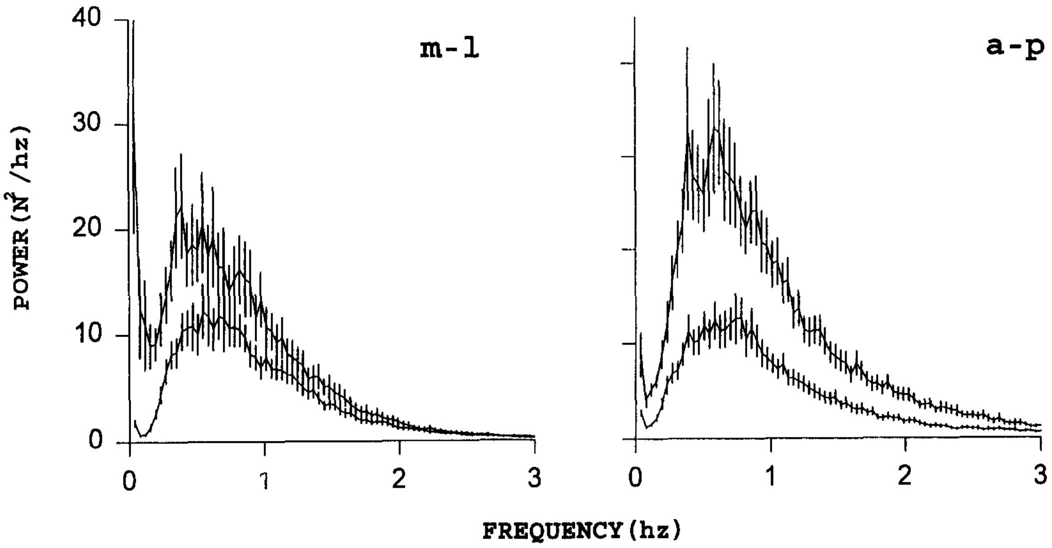

Fig. 4. Spectral envelopes generated by averaging individual spectral signatures. In both m-l and a-p directions elderly data had a greater amplitude.

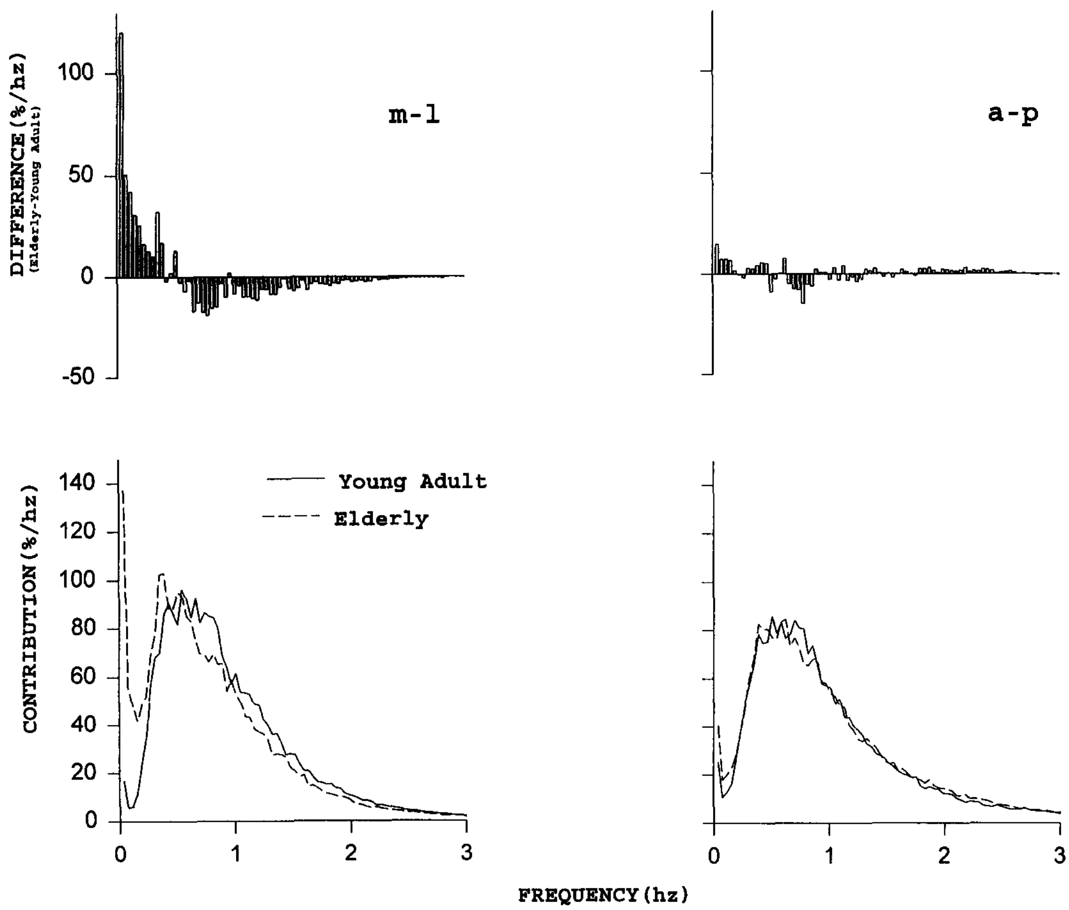

Fig. 5. Normalized spectral envelopes. Spectral signatures were normalized by their total power and averaged. The resulting normalized curves highlight the distribution of energy in the spectrum independent of amplitude.

malized to the total power contained in the spectrum. This technique was used to highlight the distribution of energy across the spectrum independent of amplitude. Data were then averaged and are presented in Fig. 5.

Elderly subjects exhibited a shift in the distribution of spectral power from higher (>0.5 Hz) to lower frequencies (<0.5 Hz) in the m-l direction. The bandwidth of spectral energy was similar for each experimental group. Elderly subjects however, exhibited the emergence of a predominant low frequency component and a subtle shift in the distribution of energy toward lower frequencies. Similar results were not observed in the a-p direction.

Age-related changes observed in the spectral characteristics of m-l forces may be related to a variety of factors associated with the aging process. The appearance of a low frequency component in the m-l postural forces, exhibited by the elderly, suggest the emergence of a slow postural drift or slow shifting of weight during static standing. The origin of this movement cannot be determined by the present study but may be related to a number of neurological and musculoskeletal declines associated with aging. Similar changes were not observed in postural forces used to maintain a-p stability.

It is possible that the different strategies used to maintain a-p vs. m-l stability may account for this difference. Anterior-posterior stability is maintained through muscular adjustments primarily at the ankle and to a lesser degree the knee and hip. Maki [49] suggested that the primary stabilizing response in the m-l direction occurred at the hip. This hip strategy was observed in a study that induced lateral perturbations to disrupt balance and examine muscular responses to instability [51]. The greater number of degrees of freedom used to maintain a-p stability provides the individual with increased alternative strategies to adjust stability and compensate for perturbations. It was suggested that age-related changes in a-p postural control may be masked by variability in the selection of a control strategy. Mizrahi and Susak [20] observed a difference in the strategy used to apply ground reaction forces between a-p and m-l directions. Anterior-posterior postural adjustments were applied to the support surface using both feet concurrently while m-l adjustments resulted from foot forces applied in opposition. These results suggest that during static standing a different strategy, ankle rotation vs. lateral weight shift, is used to maintain a-p vs. m-l stability.

These results may provide an insight into falling and the increased risk of falls associated with age. A fall occurs when stability is sufficiently disturbed to cause a loss of balance and when there is insufficient time, control and/or muscular strength to recover and/or adapt to the perturbation. Falls are complex actions that are difficult to study and therefore, little is known about the biomechanics of falling. A number of studies have focused on why people fall but few have looked at how people fall [52]. There is some indirect evidence from the present study to support the premise that age-related changes in spectral characteristics of postural forces may be an intrinsic contributor to falls.

Standing, locomotion, negotiating stairs and other activities of daily living place considerable demand on the postural system to maintain stability in the m-l direction. Adaptations to an age-related change in m-l stability can be readily observed in the fundamental movements of the elderly such as a widened stance during gait. Changes observed in the spectral measures of m-l stability may provide a marker of decreased stability associated with aging. These changes may be more evident in the shear forces associated with maintenance of static stability rather than the moments acting upon the ankle. Shear forces better represent the lateral weight shift strategy used at the hip to maintain m-l stability.

Changes in the spectral characteristics of m-l postural control may contribute to the dramatic increase in hip fractures experienced by the elderly. Ninety percent of hip fractures result from falls [52] and rarely does a fracture precede a fall [45]. Hayes et al. [52] indicated that the increased number of hip fractures exhibited by the elderly was the result of both an increased tendency to fall and the mechanics of falling. These authors reported that the location of impact was a primary contributor to hip fractures and that hip fractures were more likely to occur when an individual falls in the m-l direction. It is possible that age-related changes observed in the spectral characteristics of m-l postural control contribute to an increased susceptibility to m-l perturbations and a tendency to fall to the side.

Elderly subjects who participated in this study were healthy and did not have a history of repeated falls. Future studies should focus on subjects at higher risk of falling. Since spectral changes observed in m-l postural forces occurred at low frequencies, future studies should use longer trials to provide for greater resolution of the spectrum.

The results of this investigation also have implications for perturbation studies. Traditionally, perturbation studies have focused on horizontal or tilting movements of the support surface which result in a disturbance of a-p stability. Results of this investigation suggest emphasis also needs to be placed on perturbations that disrupt m-l stability. Results suggest that aging may influence the control of lateral stability and greater emphasis should be placed on the study of m-l postural control.

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References

[1] Ory M G, Schechtman K B, Miller J P, Hadley E C, Fiatarone M A, Province M A, Arfken C L, Morgan D, Weiss S, Kaplan M. Fraility and injuries in later life: The FICSIT trials. *J Am Gerontol Soc* 1993; 41: 283–296.

[2] Nevitt M C. Falls in older persons: Risk factors and prevention. In: *Institute of Medicine: The Second Fifty: Promoting Health and Preventing Disability*. Washington, DC: National Academy Press, 1990.

[3] Baker S P, O'Neill B, Ginsburg M J, Li G. *The Injury Fact Book*. New York: Oxford University Press, 1992.

[4] Tinetti M E, Speechley M, Ginder S F. Risk factors for falls among elderly persons living in the community. *New Engl J Med* 1988; 319: 1701–1707.

[5] Tinetti ME, Speechley M. Prevention of falls among the elderly. *New Engl J Med* 1989; 320: 1055–1059.

[6] Tideiksaar R. Falls in the elderly: a literature review. *Age* 1988; 11: 112–114.

[7] Heitmann D K, Gossman M R, Shaddeau S A, Jackson J R. Balance performance and step width in noninstitutionalized, elderly, female fallers and nonfallers. *Phys Ther* 1989; 69: 923–931.

[8] Stelmach G E, Zelaznik H N, Lowe D. The influence of aging and attentional demands on recovery from postural instability. *Aging* 1990; 2: 155–161.

[9] Woollacott M H. Age-related changes in posture and movement. *J Gerontol* 1993; 48 (Special Issue): 56–60.

[10] Tetrud J W. Preclinical detection of motor and nonmotor manifestations. *Geriatrics* 1991; 46: 43–46.

[11] Wolfson L, Whipple R, Amerman P, Tobin J N. Gait assessment in the elderly: a gait abnormality rating scale and its relation to falls. *J Gerontol: Med Sci* 1990; 45: M12–M19.

[12] Gehlsen G M, Whaley M H. Falls in the elderly: Part I, gait. *Arch Phys Med Rehabil* 1990; 71: 735–738.

[13] Tobis J S, Block M, Steinhaus-Donham C, Reinsch S, Tamaru K, Weil D. Falling among the sensorially impaired elderly. *Arch Phys Med Rehabil* 1990; 71: 144–147.

[14] Ring C, Nayak U S L, Isaacs B. Balance function in elderly people who have and have not fallen. *Arch Phys Med Rehabil* 1988; 69: 261–264.

[15] Goldstein I B, Shapiro D. Cardiovasular response during postural change in the elderly. *J Gerontol: Med Sci* 1990; 45: M20–M25.

[16] Lord S R, Clark R D, Webster I W. Postural stability and associated physiological factors in a population of aged persons. *J Gerontol: Med Sci* 1991; 46: M69–M76.

[17] Era P, Heikkinen E. Postural sway during standing and unexpected disturbance of balance in random samples of men of different ages. *J Gerontol* 1985; 287–295.

[18] Mizrahi J, Solzi P, Ring H, Nisell R. Postural stability in stroke patients: vectorial expression of asymmetry, sway activity and relative sequence of reactive forces. *Med Biol Eng Comput* 1989; 27: 181–190.

[19] Stribley R F, Albers J W, Tourtellotte W W, Cockrell J L. A quantitative study of stance in normal subjects. *Arch Phys Med Rehabil* 1974; 55: 74–80.

[20] Mizrahi J, Susak Z. Bi-lateral reactive force patterns in postural sway activity of normal subjects. *Biol Cybern* 1989; 60: 297–305.

[21] Goldie P A, Bach T M, Evans O M. Force platform measures for evaluating postural control: reliability and validity. *Arch Phys Med Rehabil* 1989; 70: 510–517.

[22] Maki B E, Holliday P J, Fernie G R. A posture control model and balance test for the prediction of relative postural stability. *IEEE Trans Biomed Eng* 1987; BME-34: 797–810.

[23] Alexander N B. Postural control in older adults. *J Am Geriatr Soc* 1994; 52: 93–108.

[24] Prieto T E, Myklebust J B, Myklebust B M. Characterization and modeling of postural steadiness in the elderly: a review. *IEEE Trans Rehabil Eng* 1993; 1: 26–34.

[25] Murry M P, Siereg A A, Sepic S B. Normal postural stability and steadiness: quantitative assessment. *J Bone Jt Surg* 1975; 57-A: 510–516.

[26] Kirshen A J, Cape R D T, Hayes H C, Spencer J D. Postural sway and cardiovascular parameters associated with falls in the elderly. *J Clin Exp Gerontol* 1984; 6: 291–307.

[27] Sheldon J H. The effect of age on the control of sway. *Gerontol Clin* 1963; 5: 129–138.

[28] Fernie G R, Gryfe C I, Holliday P J, Llewellyn A. The relationship of postural sway in standing to the incidence of falls in geriatric subjects. *Age Ageing* 1982; 11: 11–16.

[29] Overstall P M, Exton-Smith A, Imma F J, Johnson A L. Falls in the elderly related to postural imbalance. *Br Med J* 1977; 1: 261.

[30] Brocklehurst J C, Robertson D, James-Groom P. Clinical correlates of sway in old age: sensory modalities. *Age Ageing* 1982; 11: 1–10.

[31] Newell K M, van Emmerik E A, Sprague R L. Sterotypy and variability. In: Newell K M and Corcos D M, eds. *Variability and Motor Control*. Champaign, IL: Human Kinetics, 1993: 475–496.

[32] Lipsitz L A, Goldberger A L. Loss of complexity and aging: Potential applications of fractals and chaos theory to senescence. *J Am Med Assoc* 1992; 267: 1806–1809.

[33] Glass L, Mackey M C. Oscillation and chaos in physiological control systems. *Science* 1977; 197: 287–289.

[34] McClenaghan B A, Williams H G, Dickerson J, Thombs L. Use of spectral signature analysis to discriminate perturbations in standing stability: potential for identifying elderly at risk of falling. *2nd World Conference on Injury Control*, 1993 (Abstract).

[35] Smith J D. *Vibration Measurement and Analysis*. Guildford, UK: Butterworth, 1989.

[36] Fernie G R, Holliday P J. Postural sway in amputees and normal subjects. *J Bone Jt Surg* 1978; 60-A(7): 895–914.

[37] Stones M J, Kozma A. Balance and age in the sighted and blind. *Arch Phys Med Rehabil* 1987; 68: 85–88.

[38] Potvin A R, Syndulko K, Tourtellotte W W, Lemmon J A, Potvin J H. Human neurologic function and the aging process. *J Am Gerontol Soc* 1980; 28: 1–9.

[39] Hattori K, Starkes J, Takahashi T. Diurnal variability and reliability of postural sway assessment. In: Wollacott M and Horak F, eds. *Posture and Gait: Control Mechanisms, Vol. II*. Eugene, OR: University of Oregon Books, 1992: 259–262.

[40] Collins J J, De Luca C. Open-loop and closed-loop control of posture: a random-walk analysis of center of pressure trajectories. *Exp Brain Res* 1993; 95: 308–318.

[41] Cambel A B. *Applied Chaos Theory: A Paradigm for Complexity*. New York: Academic Press, 1993.

[42] Soames R W, Atha J. The spectral characteristics of postural sway behaviour. *Eur J Appl Physiol* 1982; 49: 169–177.

[43] Bensel C K, Dzendolet E. Power spectral density analysis of the standing sway of males. *Percept Psychophys* 1968; 4: 285–288.

[44] Aggashyan R V, Gurfinkel V S, Mamasakhlisov G V, Elner A M. Changes in spectral and correlation characteristics of human stabilograms at muscle afferentation disturbance. *Agressologie* 1973; 14: 5–9.

[45] Cummings S R, Rubin S M, Black D. The future of hip fractures in the United States: numbers, costs, and potential effects of postmenopausal estrogen. *Clin Orthop Relat Res* 1990; 252: 163–166.

[46] Hayes K C, Spencer J D, Riach C L, Lucy S D, Kirshen A J. Age-related changes in postural sway. In: Winter D A, Norman R W, Wells R P, Hayes K C and Patla A R, eds. *Biomechanics IX-A*. Champaign, IL: Human Kinetics, 1983: 383–387.

[47] Prieto T E, Myklebust J B, Myklebust B M, Kreis D U. Intergroup sensitivity in measures of postural steadiness. In: Woollacott M and Horak F, eds. *Posture and Gait: Control Mechanisms 1992*. Eugene, OR: University of Oregon Books, 1992: 122–125.

[48] Taguchi K. Spectral analysis of the movement of the center of gravity in vertiginous and ataxic patients. *Agressologie* 1978; 19: 69–70.

[49] Maki B E, Holliday P J, Topper A K. Postural control and prospective risk of falling in the elderly. In: Woolacott M and Horak F, eds. *Posture and Gait: Control Mechanisms 1992*. Eugene, Oregon: University of Oregon Books, 1992: 291–294.

[50] Maki B E, Holliday P J, Topper A K. A prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. *J Gerontol: Med Sci* 1994; 49: M72–M84.

[51] Moore S P, Rushmer D S, Windus S L, Nashner L M. Human automatic postural responses: responses to horizontial perturbations of stance in multiple directions. *Exp Brain Res* 1988; 73: 648–658.

[52] Hayes W C, Myers E R, Morris J N, Gerhart T N, Yett H S, Lipsitz L A. Impact near the hip dominates fracture risk in elderly nursing home residents who fall. *Calcif Tissue Int* 1993; 52: 192–198.