AGE-RELATED CHANGES IN HUMAN POSTURE CONTROL: MOTOR COORDINATION TESTS

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Postural responses to support surface displacements were measured in 214 normal human subjects ranging in age from 7 to 81 years. Motor tests measured leg muscle EMG latencies, body sway, and the amplitude and timing of changes in center of pressure displacements in response to sudden forward and backward horizontal translations of the support surface upon which the subjects stood. There were small increases in both EMG latencies and the time to reach the peak amplitude of center of pressure responses with increasing age. The amplitude of center of pressure responses showed little change with age if the amplitude measures were normalized by a factor related to subject height. In general, postural responses to sudden translations showed minimal changes with age, and all age-related trends which were identified were small relative to the variability within the population.

Key Words: posturography, EMG, coordination, equilibrium, development.

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INTRODUCTION

If the posture of a quietly standing individual is suddenly perturbed by the application of an external force, rapid automatic responses are initiated which maintain postural equilibrium (1). These postural responses produce compensatory muscle contractions beginning about 100 ms following the start of the perturbation. Experimental tests of postural motor coordination typically measure postural reactions to short duration translations or rotations of the support surface upon which the subject stands (2,3,4,5). A consistent finding has been a coordinated synergy in which muscle contraction proceeds from distal to proximal leg and trunk muscles following a support surface perturbation.

Various factors associated with the visual, vestibular, and somatosensory systems have been shown to influence or modulate these responses. These factors include support surface condition (6), initial body position (4,7), stimulus velocity and displacement amplitudes (8), galvanic stimulation to the inner ear (9), and availability of visual (10) and proprioceptive cues (11).

The complexity of maintaining upright stance suggests that there would be a great deal of functional variability within a normal population as a result of variations in sensory system, central nervous system, and biomechanical function in individuals. Systematic changes may also occur as a result of childhood development and degeneration associated with aging. In order to define the range of normal function, and to identify the nature of

any age-related changes in postural motor coordination, we tested a putatively normal population with a wide age distribution.

METHODS

Posture coordination function was tested in 214 human subjects (90 male and 124 female) aged 7 to 81 years. Ages were approximately uniformly distributed over the entire range. Rotation tests of horizontal vestibulo-ocular and optokinetic reflex function, caloric tests, and sensory interaction tests of postural control were measured in these same subjects on the same day, and are reported in companion papers (12,13,14). Details of subject selection are given in a previous paper (13). Subjects were not excluded from the population based on any vestibular, optokinetic, or posture test results.

Subjects stood on a movable support surface surrounded in front and on two sides by a visual surround which was stationary during motor tests. The visual surround was a box with randomly placed 2 cm black dots on a white surface. The average spacing between the dots was about 20 cm, and the distance from the subject to the box was about 50 cm. Support surface motion was controlled by a hydraulic position servo system which could produce toe up and toe down rotations about an axis collinear with the subject's ankle joints, and forward and backward translations. Force transducers in the support surface recorded vertical forces applied by each of the subject's legs. The anterior-posterior (AP) sway angle (θ_{ap}) of each subject was recorded using a rod attached to a

potentiometer. The potentiometer was mounted on a post next to the subject. The end of the rod rested in a V-shaped holder centered on the subject's back at hip level. A voltage proportional to the rotation of the potentiometer was recorded and later transformed using appropriate trigonometric conversions to θ_{ap}.

Tests consisted of five each of forward platform translations, toe down rotations, backward translations, and toe up rotations of the support surface on which the subject stood with eyes open viewing the stationary visual surround. Only responses to translations are reported in this paper. Ramp translations were 3 cm in 0.25 s. The support surface returned slowly to the center position following each motion and there was a variable delay averaging 4 s between stimuli. Four EMG's were recorded from the left leg using surface electrodes over the gastrocnemius (G), tibialis anterior (T), hamstring (H), and quadriceps (Q) muscles. EMG's were rectified, low pass filtered at 20 Hz, and sampled at 500 Hz. The latency to the onset of the reflex EMG bursts were estimated from average EMG traces. Latencies were recorded from averaged traces only if the EMG onset times could unambiguously be separated from background activity. Consequently the number of subjects contributing to the data sets in various figures and tables varies.

AP displacement of each subject's center of pressure (CP with units of cm) was calculated for each leg by the following formula:

$$CP = \frac{L(F_f - F_b)}{F_f + F_b}$$

where L is the length from the ankle joint to the front and to the back force transducers in the platform, and F_f and F_b are the vertical forces recorded by the front and back force transducers during the trial. The center of pressure velocity (CPV in cm/s) was computed from CP by a two point central difference formula. The CP and CPV traces from five trials were averaged, and various peak amplitude and time parameters were measured for each subject (Figure 1). All EMG, CP, CPV, and θ_{ap} times were referenced to the start of platform motion as determined by the earliest deviation of the average CP trace from its baseline.

In order to visualize trends in various scatterplots, a robust locally weighted regression analysis (lowess fit) was used to smooth the scatterplots (15). Lowess smoothing is similar to a moving average but is less influenced by values far from the central tendency of the data. The degree of smoothing is specified by a smoothing parameter (f) between 0 and 1. Larger f values give more smoothing.

RESULTS

General Response Pattern. Figure 1 shows typical EMG, CP, CPV, and θ_{ap} response patterns for one subject during a 3 cm backward translation. The backward support surface translation results in forward body sway with respect to the platform. In the first 100 ms, the CP movement away from baseline is probably the result of passive properties of body biomechanics combined with artifacts of

the platform force recording system. About 110 ms following the start of the translation, the distal leg muscles (gastrocnemius) which oppose the forward body sway begin to contract as evidenced by EMG recordings. The proximal leg muscles (hamstrings) begin to contract about 20-30 ms following the distal muscles. The dorsal leg muscle contractions generate torque about the ankle joint which causes a forward displacement of CP. The onset of the active torque generation (CP_o) begins about 130 ms after the start of platform translation. CP reaches a peak displacement amplitude (CP_a) at about 230 ms (CP_t). Sway (θ_{ap}) reaches a peak (θ_a) at about 260 ms (θ_t) and then returns toward an upright position. The time (CPV_t) of the CPV peak amplitude (CPV_a) occurs between CP_o and CP_t.

Forward support surface translations causing backward sway with respect to the platform initiate contractions of the T and Q muscles. The patterns of sway and changes in CP are similar to those for backward translations, but have opposite sign.

The population statistics describing EMG onset times, CP_o, CP_t, CPV_t, θ_t, CP_a, CPV_a, and θ_a are given in Table 1. The values of all EMG onsets, CP_o, and CPV_t were symmetrically distributed about their means. CP_a and CPV_a distributions were slightly skewed toward larger values. Most values of θ_t for both forward and backward translations were tightly grouped around 260 ms but about 15% of the population had values of θ_t of about 375 ms. θ_t for backward translations included a scattering of times shorter than 260 ms. CP_t for both forward and backward translations also showed bimodal distributions. For backward translations, 82% of

the subjects had both right and left leg CP_t's centered about a mean of 245 ms, 11% had both right and left CP_t's centered about 360 ms, and the remainder of the population had one leg's CP_t less than 300 ms and the other greater than 300 ms. For forward translations, 49% of the subjects had both right and left leg CP_t's centered about a mean of 260 ms, 34% had both right and left CP_t's centered about 350 ms, and the remainder of the population had one leg's CP_t less than 300 ms and the other greater than 300 ms.

For both forward and backward translations, subjects with shorter CP_t's (<300 ms) had larger mean values of CPV_a and smaller mean values of CP_o and CPV_t (all significant at $P<0.01$) than subjects with longer CP_t's (>300 ms). For backward but not forward translations, mean CP_a were also significantly larger for the short CP_t group. There was no clear relation between the bimodality of the θ_t and CP_t distributions. That is, many subjects with larger CP_t's had smaller θ_t's, and other subjects with smaller CP_t's had larger θ_t's.

The response pattern from three subjects during backward translation and two subjects during forward translation did not allow for accurate estimation of the various center of pressure and sway parameters. In all these cases there appeared to be little or no active torque generated by the subjects.

Age-Related Changes in EMG Onsets. With the exception of quadriceps, EMG onset times generally increased with increasing subject age (Figure 2A-D). Linear fits to the data (Table 2) showed that the rate of change of EMG onset times with age were

0.21 ms/year for G, 0.30 for H, 0.10 for T, and -0.07 for Q with linear correlation coefficients of r=0.335, 0.267, 0.158, and -0.075 for G_o, H_o, T_o, and Q_o respectively. However the lowess fits to G_o, T_o, and H_o suggested that there may be an inflection point at about age 55 with a larger rate of change for subjects older than 55 years. To compare the rates for younger and older subjects, two part linear fits were made to G_o, H_o, and T_o for subjects younger and older than 55 years with the constraint that the two linear fits intersect at age 55 years. The slopes for younger vs older subjects were 0.17 vs 0.40, 0.14 vs 0.83, and 0.02 vs 0.45 ms/year for G_o, H_o, and T_o respectively. The slowing of motor responses in the older age group was most evident in the T responses since there was a transition from essentially no trend with age for subjects younger than 55 years to a slope comparable to the G_o and H_o data.

The difference between the EMG onset times for the H and G muscles (H_o-G_o) during backward translations, and between Q and T muscles (Q_o-T_o) during forward translations is plotted as a function of subject age in Figure 2E and F. There was a small increase in the H_o-G_o delay with increasing age (0.17 ms/year with r=0.185). For the Q_o-T_o delay, subjects younger than 20 years tended to have larger Q_o-T_o delays (mean 22.2 ms ± 22.0 s.d.) than subjects older than 20 years (mean 9.6 ms ± 18.0 s.d.). The difference in mean Q_o-T_o between these two groups is significant (P<0.01). The larger Q_o-T_o delays for younger compared to older subjects is the result of (1) later Q_o values for younger subjects (Figures 2D) and (2) the upward trend in T_o with age, particularly

for older subjects, coupled with essentially no age trend for Q_o in subjects older than 20 years.

Age Related Changes in CP and CPV. Figure 3 shows CP_a, CP_t, CPV_a, CPV_t, and CP_o as a function of age from backward translations recorded from the right leg. In addition, CP_a normalized by dividing by the square of subject height in meters is also plotted. Table 2 summarizes linear regression fits to CP_t, CPV_t, and CP_o data versus age. Linear regressions to CP_t were restricted to the larger group of subjects whose CP_t's were less that 300 ms.

CP_t, CPV_t, and CP_o for backward translations, and CP_t for forward translations showed small (0.2 ms/year) approximately linear increases with increasing age. CPV_t and CP_o for forward translations did not change significantly with age.
Values of CP_a and CPV_a for subjects older than about 20 years did not show any consistent trend. However CP_a and CPV_a for subjects younger than 20 years showed large increases with increasing age in both forward and backward translations (Table 2). Normalizing CP_a and CPV_a by the square of the individual subjects' heights (h^2) removed most of the age-related trends in CP_a and CPV_a in the younger subjects indicating that the source of this trend was probably related to changes in body dimensions with growth. Normalization by h^2 also reduced the entire population's variability of CP_a relative to the mean value. For example, the coefficient of variation (CV = s.d./mean) of CP_a from right leg backward translations was 0.98 while the CV of CP_a/h^2 was 0.29. The normalization only slightly reduced the CV of CPV_a from 0.44

to 0.41. Normalization of CP_a by h^2 theoretically provides a value proportional to the peak rotational acceleration of the body about the ankle joint (see Discussion).

Right-Left Asymmetry. Table 3 summarizes comparisons between measures of CP_a, CP_t, CPV_a, CPV_t, and CP_o recorded from the right and left legs during forward and backward translations. The CP_a and CPV_a responses from the left leg were significantly larger than the right during backward, but not forward translations. With the exception of forward translation CP_t, in which right side responses were longer than left, there were no significant timing differences between right and left leg responses.

Comparison of EMG and CP Timing. Table 4 summarizes the correlations between EMG onset times, and the various measures of CP and sway times including CP_o, CP_a, CP_t, CPV_t, and θ_t. The average of right and left leg responses of CP_o, CP_t, and CPV_t were used in the calculations. The bimodal distributions of CP_t and θ_t distorted the correlation analysis when data from all subjects were included, therefore the analysis was restricted to the larger portion of the population with shorter CP_t and θ_t responses.

In general, there were moderate, positive correlations between the various response timing measures. For both forward and backward translations, the largest correlations were between CP_o and CPV_t. The largest correlation between any EMG and CP parameters was between T_o and CP_o for forward translations. θ_t correlations with other response time parameters were smaller than most other comparisons.

The interpretation of this correlation analysis is potentially problematic since different subsets of the population contributed to different correlation measures. However a correlation analysis which included only subjects with no missing values gave similar results.

Forward - Backward Translation Comparison. Table 1 shows that CP_o, CP_t, CPV_t, and θ_t response times were larger for forward than backward translations even though T_o and Q_o times were similar, and even slightly shorter than G_o and H_o times. In addition, the timing difference between forward and backward translations increases for parameters which occur later in the normal sequence of motion. That is, EMG timing is similar, CP_o is 10 ms later, CPV_t is 13 ms later, and CP_t and θ_t are about 30 ms later for forward compared to backward translations.

Response amplitude measures also differed between forward and backward translations. Both CP_a and CPV_a were significantly larger for backward translations, and θ_t was larger for forward translations (all $P<0.0001$, paired t-test). This pattern is consistent with the generation of less corrective torque on forward translations compared to backward, resulting in larger peak body sway from forward platform motions.

DISCUSSION

Most of the results of motor tests of postural control showed a wide range of what must be considered normal function. In spite of the large variances, small age-related changes in function were

evident in some response parameters. The latency of EMG onsets, with the exception of quadriceps, following support surface translations increased with increasing age. In addition, there was evidence that the rate of increase of EMG onset with age was larger for subjects older than about 55 years. This increased rate was most evident in the tibialis muscle. Studies of muscle strength in the elderly (16) have also shown proportionally larger losses in tibialis strength compared to other leg muscles. The loss of strength combined with the slowing of the tibialis muscle response to body perturbations would diminish an individual's ability to control backward sway.

The distal before proximal muscle contraction synergy was observed in most subjects. However during forward translations, Q_o preceded T_o in about 25% of the subjects. This may be related to initial knee position which was not carefully controlled. For example, if the knees of some subjects were slightly flexed prior to the translation, an early Q contraction would hyperextend the knee and pull the lower part of the trunk slightly forward. A previous study (17) also noted that some subjects had reversed Q_o-T_o timing. However, in that study the reversal was only found in their older subjects. Figure 2F shows that Q_o-T_o reversal occurred across the entire age range, although there was a slightly larger incidence in older subjects.

Normalization of CP_a and CPV_a by the square of subject height (h^2) both removed a large age-related trend for subjects under 20 years, and reduced the variability relative to the mean of CP_a for the entire population. The rationale for this normalization

relates to the mechanics of movement. In order to correct for an external perturbation which causes AP sway, a subject exerts a torque, T, about the ankle joint. This torque produces a rotational acceleration, α, according to $\alpha=T/I$ where I is the moment of inertia of the subject. I is related to the mass distribution of the subject relative to the rotation axis (ankle joint). Using the simplifying assumption that all of the subject's mass, m, is located at the center of mass (about hip level), then $I=mr^2$ where r is the distance from the ankle joint to the center of mass. The calculation of CP gives a value proportional to T/m. Dividing CP by h^2 gives a value proportional to T/I and to α since r^2 is proportional to h^2. CP_a/h^2 data versus age is fairly constant indicating that the peak angular acceleration of body sway in response to a sudden translation changes little with age.

Postural motor coordination tests similar to those described here are increasingly being used for clinical evaluation. For patients with balance disorders, these motor tests serve a function similar to optokinetic and pursuit tests for the evaluation of the ascending visual and visual-vestibular system control of eye movements. That is, they provide information on the integrity of spinal and central nervous system function important for the interpretation of sensory organization tests of postural control (12).

The clinical use of postural motor coordination tests requires an appropriate selection of response parameters and a definition of the range of these parameters in a normal population. Ideally

these parameters should have narrow distributions for normal subjects, and should be sensitive to abnormalities. This paper does not address abnormal response patterns, but the results do suggest that some of the potential motor response parameters may be difficult to use clinically. In general, the variability of the parameters was large even though age-related trends contributed very little to the variability. Among timing measures, G_o and CP_o for backward translations and T_o for forward translations showed the least variability, followed by Q_o and CP_o for forward, H_o for backward, and CPV_t for both forward and backward translations. Despite their narrower distributions, EMG onset times are problematic in routine clinical tests since they are often difficult to measure.

The bimodal distributions of CP_t and θ_t make them less attractive candidates for clinical functional measures. Although there were differences between some motor response measures related to the bimodal distributions of CP_t, there was no clear indication of the source(s) of these bimodal responses. Perhaps the support surface perturbations evoked different movement patterns in different subjects with some subjects moving like inverted pendulums, while others used more complex motions to maintain their upright posture.

Among response amplitude measures, there appeared to be little range for abnormally low CP_a and CPV_a responses since many subjects in our putatively normal population showed responses only slightly above the passive-platform artifact level. Different force platform designs with smaller mechanical artifacts might

improve the separation of abnormal subjects from normal subjects with low amplitude responses. CP_a and CPV_a values normalized by h^2 were better parameters for comparisons across populations than CP_a and CPV_a alone.

Different mechanical platform systems, instrumentation, data analysis, and particularly, stimulus parameters, could influence the conclusions drawn in this paper. As other motor coordination tests with different stimulus conditions are developed, it will be important to consider the possible presence of bimodal parameter distributions, to determine the neural or biomechanical factors which cause these bimodal responses, and to test a large enough population to clearly define the range of normal function.

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Table 1. EMG, CP, CPV, and θ_{ap} parameters (mean ± 1 s.d.).

		Backward			Forward		
	units	Right	Left	N	Right	Left	N
G_o	ms		115±12.9	182			
H_o	ms		145±22.5	168			
T_o	ms		114±13.4	206			
Q_o	ms		126±19.6	147			
CP_o	ms	127±13.1	127±14.1	211	137±23.1	137±24.5	212
CPV_t	ms	167±17.2	166±18.2	211	180±39.7	176±32.0	212
CP_t	ms	261±46.5	262±43.7	211	297±56.5	291±55.3	212
θ_t	ms		259±55.9	211		289±44.2	212
CP_a	cm	1.31±0.42	1.42±0.46	211	1.24±0.40	1.23±0.39	212
CP_a/h^2	cm/m^2	0.46±0.13	0.50±0.14	198	0.44±0.12	0.43±0.13	199
θ_a	degrees		1.62±0.37	211		1.88±0.31	212

Table 2. Linear regression and correlation coefficients for EMG, CP, CPV, and θ_{ap} parameters versus age. Units are the same as in Table 1.

	Backward Translation				Forward Translation			
	slope (change/year)	intercept	r	N	slope (change/year)	intercept	r	N
G_o	0.21	107	0.335*	182				
H_o	0.30	132	0.267*	168				
T_o					0.10	110	0.158*	206
Q_o					-0.07	129	-0.075	147
CP_o	0.16	121	0.263*	211	-0.06	139	-0.057	212
CP_t[a]	0.15	238	0.186*	172	0.34	239	0.324*	104
CPV_t	0.21	158	0.262*	211	-0.10	182	-0.063	212
θ_t[b]	0.31	233	0.146	189	0.08	265	0.191*	171
CP_a								
age<20y	0.11	-0.27	0.687*	46	0.06	0.15	0.554*	46
age≥20y	-0.004	1.59	-0.156	165	0.001	1.24	0.062	166
CPV_a								
age<20y	1.26	-2.89	0.522*	46	0.66	1.27	0.468*	46
age≥20y	-0.05	17.4	-0.129	165	0.009	12.0	0.034	166
CP_a/h^2	0.0004	0.47	0.071	198	0.002	0.36	0.333*	199
CPV_a/h^2	0.0017	5.10	0.018	198	0.015	3.54	0.226*	199
θ_a	-0.002	1.71	-0.094	211	-0.002	1.95	-0.114	211

a Only includes values with both R and L CP_t's < 300 ms

b Only includes θ_t's < 300 ms

* Correlation coefficients significantly different from zero ($P<0.05$)

Table 3. Percent asymmetry and absolute difference between right and left motor response parameters. All values are mean ± 1 s.d., N's are 211 subjects for backward and 212 for forward translations. A nonparametric Wilcoxon signed rank statistic was used to test for significant R-L differences from zero for CP_t and CPV_t. A paired variable t-test was used for the same purpose on all other variables. All values with P<0.05 are indicated.

		Backward		Forward	
	units	100(R-L)/(R+L)	R-L	100(R-L)/(R+L)	R-L
CP_a	(cm)	-4.3 ±12.5	-0.12±0.33**	0.4 ± 0.9	0.01 ±0.27
CPV_a	(cm/s)	-5.1 ±14.5	-1.4 ± 4.1**	0.5 ± 12.8	0.0 ±3.0
CP_t	(ms)	-0.3 ± 5.1	-1.4 ± 30.1	1.0 ± 7.0	6.0 ± 41.2*
CPV_t	(ms)	0.2 ± 4.1	0.5 ± 14.0	0.9 ± 7.3	4.4 ± 31.6
CP_o	(ms)	-0.2 ± 4.1	-0.5 ± 10.4	-0.2 ± 4.7	-0.9 ± 13.6

* P<0.005
** p<0.0001

Table 4. Correlation coefficients comparing motor response times.

Backward Translation

	H_o		CP_o		CPV_t		CP_t[a]		θ_t[b]	
	r	N	r	N	r	N	r	N	r	N
G_o	0.380	145	0.366	181	0.370	181	0.331	149	0.217	163
H_o			0.338	167	0.412	167	0.273	138	0.253	148
CP_o					0.606	211	0.396	172	0.311	189
CPV_t							0.500	172	0.246	189
CP_t[a]									0.360	159

Forward Translation

	Q_o		CP_o		CPV_t		CP_t[a]		θ_t[b]	
	r	N	r	N	r	N	r	N	r	N
T_o	0.338	147	0.544	205	0.484	205	0.122	101	0.226	166
Q_o			0.394	147	0.205	147	-0.082	76	0.081	120
CP_o					0.630	212	0.202	104	0.123	171
CPV_t							0.337	104	0.165	171
CP_t[a]									0.156	89

a Only includes values with R and L CP_t's < 300 ms
b Only includes θ_t's < 300 ms

FIGURE LEGENDS

Figure 1. Average EMG, CP, CPV, and θ_{ap} responses of one individual to five consecutive backward support surface translations. Arrows indicate the various amplitude and time parameters used to quantify responses.

Figure 2. EMG onset times (A, B, C, D) from support surface translations as a function of subject age, and the difference between proximal and distal EMG onset times (E, F) as a function of age. Plots are based on recordings from 182, 168, 206, and 147 subjects for G_o, H_o, T_o, and Q_o, and 145 and 147 for H_o-G_o and Q_o-T_o respectively. Solid lines through data are lowess fits with f=0.5.

Figure 3. Various motor response amplitude (A, C, E) and time (B, D, F) parameters as a function of subject age. All plots are from backward translation responses from the right leg. Solid lines through data are lowess fits with f=0.3.

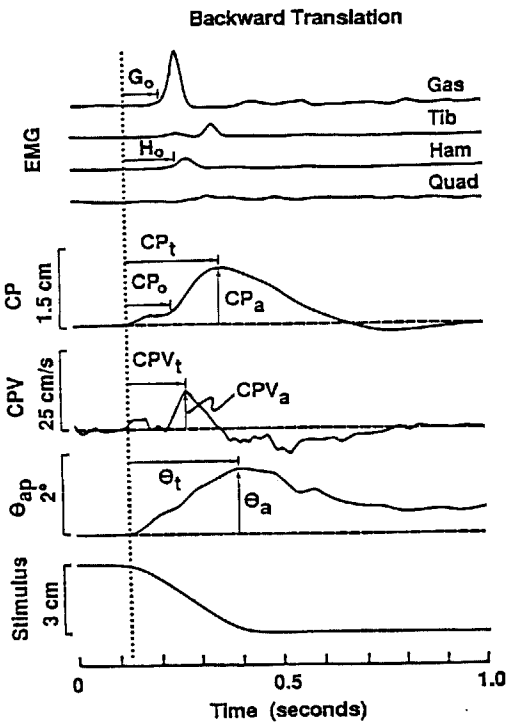

Figure 1

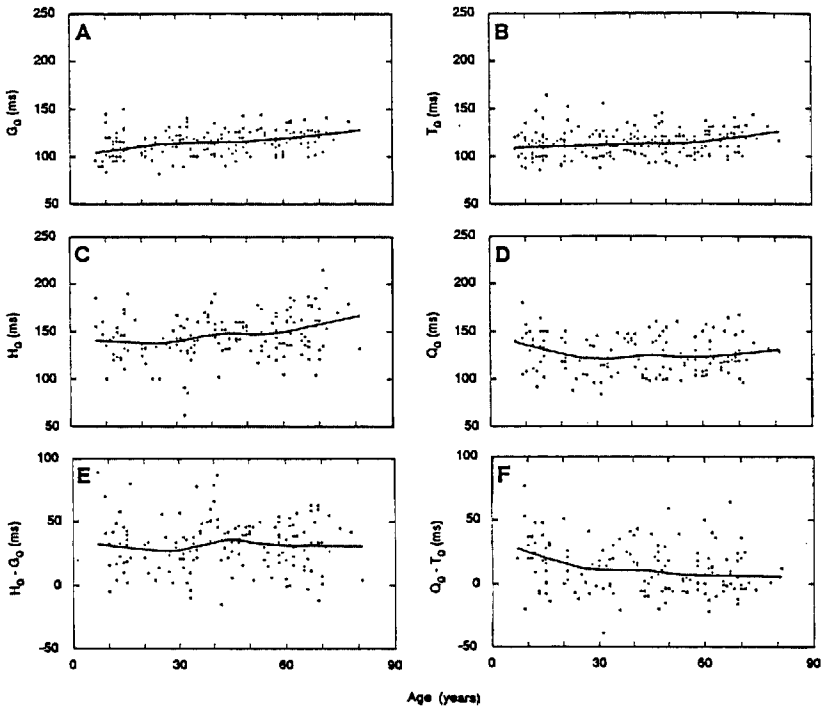

Figure 2

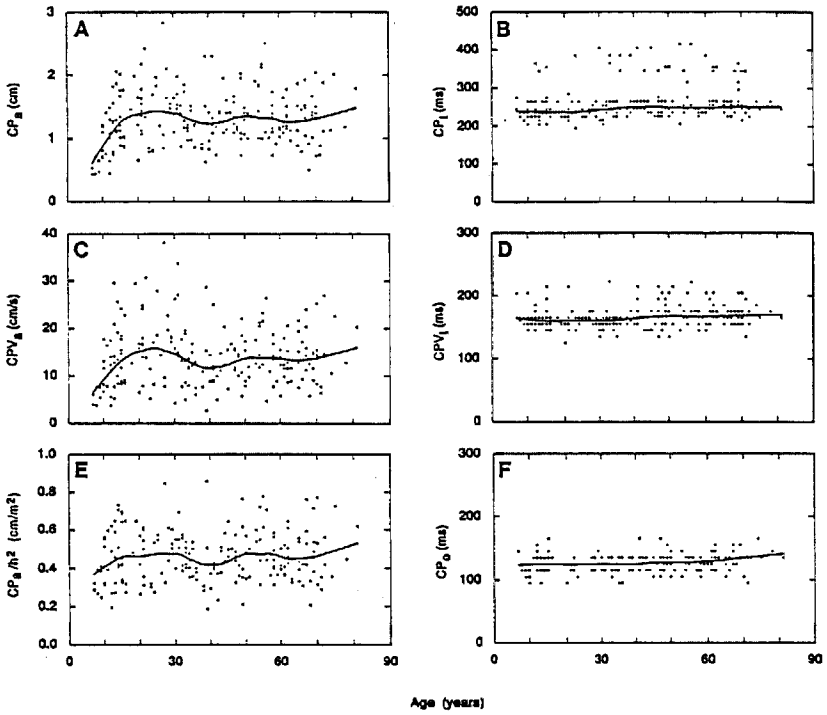

Figure 3