

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 ( $\theta_{ap}$ ) 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  $\theta_{ap}$ .

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  $\theta_{ap}$  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  $\theta_{ap}$  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 ( $CP_0$ ) 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 ( $\theta_{ap}$ ) reaches a peak ( $\theta_A$ ) at about 260 ms ( $\theta_t$ ) and then returns toward an upright position. The time ( $CPV_t$ ) of the CPV peak amplitude ( $CPV_A$ ) occurs between  $CP_0$  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,  $CP_0$ ,  $CP_t$ ,  $CPV_t$ ,  $\theta_t$ ,  $CP_A$ ,  $CPV_A$ , and  $\theta_A$  are given in Table 1. The values of all EMG onsets,  $CP_0$ , and  $CPV_t$  were symmetrically distributed about their means.  $CP_A$  and  $CPV_A$  distributions were slightly skewed toward larger values. Most values of  $\theta_t$  for both forward and backward translations were tightly grouped around 260 ms but about 15% of the population had values of  $\theta_t$  of about 375 ms.  $\theta_t$  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  $CP_0$  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  $\theta_t$  and  $CP_t$  distributions. That is, many subjects with larger  $CP_t$ 's had smaller  $\theta_t$ 's, and other subjects with smaller  $CP_t$ 's had larger  $\theta_t$ '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  $G_0$ ,  $H_0$ ,  $T_0$ , and  $Q_0$  respectively. However the lowest fits to  $G_0$ ,  $T_0$ , and  $H_0$  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  $G_0$ ,  $H_0$ , and  $T_0$  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  $G_0$ ,  $H_0$ , and  $T_0$  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  $G_0$  and  $H_0$  data.

The difference between the EMG onset times for the H and G muscles ( $H_0-G_0$ ) during backward translations, and between Q and T muscles ( $Q_0-T_0$ ) during forward translations is plotted as a function of subject age in Figure 2E and F. There was a small increase in the  $H_0-G_0$  delay with increasing age ( $0.17$  ms/year with  $r=0.185$ ). For the  $Q_0-T_0$  delay, subjects younger than 20 years tended to have larger  $Q_0-T_0$  delays (mean  $22.2$  ms  $\pm 22.0$  s.d.) than subjects older than 20 years (mean  $9.6$  ms  $\pm 18.0$  s.d.). The difference in mean  $Q_0-T_0$  between these two groups is significant ( $P<0.01$ ). The larger  $Q_0-T_0$  delays for younger compared to older subjects is the result of (1) later  $Q_0$  values for younger subjects (Figures 2D) and (2) the upward trend in  $T_0$  with age, particularly

for older subjects, coupled with essentially no age trend for  $Q_0$  in subjects older than 20 years.

*Age Related Changes in CP and CPV.* Figure 3 shows  $CP_a$ ,  $CPT$ ,  $CPV_a$ ,  $CPV_t$ , and  $CP_0$  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  $CPT$ ,  $CPV_t$ , and  $CP_0$  data versus age. Linear regressions to  $CPT$  were restricted to the larger group of subjects whose  $CPT$ 's were less than 300 ms.

$CPT$ ,  $CPV_t$ , and  $CP_0$  for backward translations, and  $CPT$  for forward translations showed small ( $0.2$  ms/year) approximately linear increases with increasing age.  $CPV_t$  and  $CP_0$  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  $\theta_t$ . 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  $\theta_t$  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  $\theta_t$  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.  $\theta_t$  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  $\theta_t$  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  $\theta_t$  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  $\theta_t$  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,  $Q_0$  preceded  $T_0$  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  $Q_0$ - $T_0$  timing. However, in that study the reversal was only found in their older subjects. Figure 2F shows that  $Q_0$ - $T_0$  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,  $\alpha$ , 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  $\alpha$  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,  $G_0$  and  $CP_0$  for backward translations and  $T_0$  for forward translations showed the least variability, followed by  $Q_0$  and  $CP_0$  for forward,  $H_0$  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  $\theta_t$  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  $\theta$ ap parameters (mean  $\pm$  1 s.d.).

units	Backward		Forward	
	Right	Left	Right	Left
Go		115 $\pm$ 12.9		
H <sub>0</sub>		145 $\pm$ 22.5		
To		114 $\pm$ 13.4		
Q <sub>0</sub>		126 $\pm$ 19.6		
CP <sub>0</sub>	127 $\pm$ 13.1	127 $\pm$ 14.1	137 $\pm$ 23.1	137 $\pm$ 24.5
CPV <sub>t</sub>	167 $\pm$ 17.2	166 $\pm$ 18.2	180 $\pm$ 39.7	176 $\pm$ 32.0
CP <sub>t</sub>	261 $\pm$ 46.5	262 $\pm$ 43.7	297 $\pm$ 56.5	291 $\pm$ 55.3
$\theta_t$		259 $\pm$ 55.9		289 $\pm$ 44.2
CP <sub>a</sub>	1.31 $\pm$ 0.42	1.42 $\pm$ 0.46	1.24 $\pm$ 0.40	1.23 $\pm$ 0.39
CP <sub>a</sub> /h <sup>2</sup>	0.46 $\pm$ 0.13	0.50 $\pm$ 0.14	0.44 $\pm$ 0.12	0.43 $\pm$ 0.13
$\theta_a$		1.62 $\pm$ 0.37		1.88 $\pm$ 0.31

Table 2. Linear regression and correlation coefficients for EMG, CP, CPV, and  $\theta$ 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
Go	0.21	107 0.335* 182		
H <sub>0</sub>	0.30	132 0.267* 168		
To			0.10	110 0.158* 206
Q <sub>0</sub>			-0.07	129 -0.075 147
CP <sub>0</sub>	0.16	121 0.263* 211	-0.06	139 -0.057 212
CP <sub>t</sub> <sup>a</sup>	0.15	238 0.186* 172	0.34	239 0.324* 104
CPV <sub>t</sub>	0.21	158 0.262* 211	-0.10	182 -0.063 212
$\theta_t$ <sup>b</sup>	0.31	233 0.146 189	0.08	265 0.191* 171
CP <sub>a</sub>				
age<20y	0.11	-0.27 0.687* 46	0.06	0.15 0.554* 46
age $\geq$ 20y	-0.004	1.59 -0.156 165	0.001	1.24 0.062 166
CPV <sub>a</sub>				
age<20y	1.26	-2.89 0.522* 46	0.66	1.27 0.468* 46
age $\geq$ 20y	-0.05	17.4 -0.129 165	0.009	12.0 0.034 166
CP <sub>a</sub> /h <sup>2</sup>	0.0004	0.47 0.071 198	0.002	0.36 0.333* 199
CPV <sub>a</sub> /h <sup>2</sup>	0.0017	5.10 0.018 198	0.015	3.54 0.226* 199
$\theta_a$	-0.002	1.71 -0.094 211	-0.002	1.95 -0.114 211

<sup>a</sup> Only includes values with both R and L CP<sub>t</sub>'s < 300 ms

<sup>b</sup> Only includes  $\theta_t$ '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  $\pm$  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<sub>t</sub> and CPV<sub>t</sub>. A paired variable t-test was used for the same purpose on all other variables. All values with P<0.05 are indicated.

units	Backward		Forward	
	$100(R-L)/(R+L)$	R-L	$100(R-L)/(R+L)$	R-L
CP <sub>a</sub> (cm)	-4.3 $\pm$ 12.5	-0.12 $\pm$ 0.33**	0.4 $\pm$ 0.9	0.01 $\pm$ 0.27
CPV <sub>a</sub> (cm/s)	-5.1 $\pm$ 14.5	-1.4 $\pm$ 4.1**	0.5 $\pm$ 12.8	0.0 $\pm$ 3.0
CP <sub>t</sub> (ms)	-0.3 $\pm$ 5.1	-1.4 $\pm$ 30.1	1.0 $\pm$ 7.0	6.0 $\pm$ 41.2*
CPV <sub>t</sub> (ms)	0.2 $\pm$ 4.1	0.5 $\pm$ 14.0	0.9 $\pm$ 7.3	4.4 $\pm$ 31.6
CP <sub>o</sub> (ms)	-0.2 $\pm$ 4.1	-0.5 $\pm$ 10.4	-0.2 $\pm$ 4.7	-0.9 $\pm$ 13.6

\* P&lt;0.005

\*\* P&lt;0.0001

Table 4. Correlation coefficients comparing motor response times.

## Backward Translation

	$\frac{H_o}{r}$	$\frac{CP_o}{N}$	$\frac{CPV_t}{N}$	$\frac{CP_t^a}{N}$	$\frac{\theta_t^b}{N}$
G <sub>o</sub>	0.380	0.366	0.370	0.331	0.217
H <sub>o</sub>	145	181	181	149	163
CP <sub>o</sub>	0.338	0.367	0.412	0.273	0.253
CPV <sub>t</sub>			0.606	0.396	0.311
CP <sub>t</sub> <sup>a</sup>			0.500	0.500	0.246
					0.360
					159

## Forward Translation

	$\frac{Q_o}{r}$	$\frac{CP_o}{N}$	$\frac{CPV_t}{N}$	$\frac{CP_t^a}{N}$	$\frac{\theta_t^b}{N}$
T <sub>o</sub>	0.338	0.544	0.484	0.122	0.226
Q <sub>o</sub>	147	205	205	101	166
CP <sub>o</sub>	0.394	0.544	0.205	-0.082	0.081
CPV <sub>t</sub>		0.630	0.202	0.202	0.123
CP <sub>t</sub> <sup>a</sup>			0.337	0.337	0.165
					0.156
					89

\* Only includes values with R and L CP<sub>t</sub>'s < 300 msb Only includes  $\theta_t$ 's < 300 ms

## FIGURE LEGENDS

Figure 1. Average EMG, CP, CPV, and  $\theta_{ap}$  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 Go, Ho, To, and Qo, and 145 and 147 for Ho-Go and Qo-To 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  $f=0.3$ .

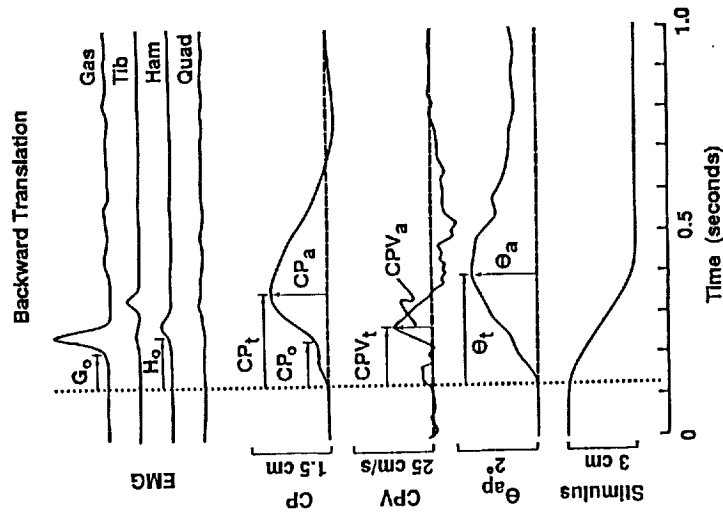


Figure 1

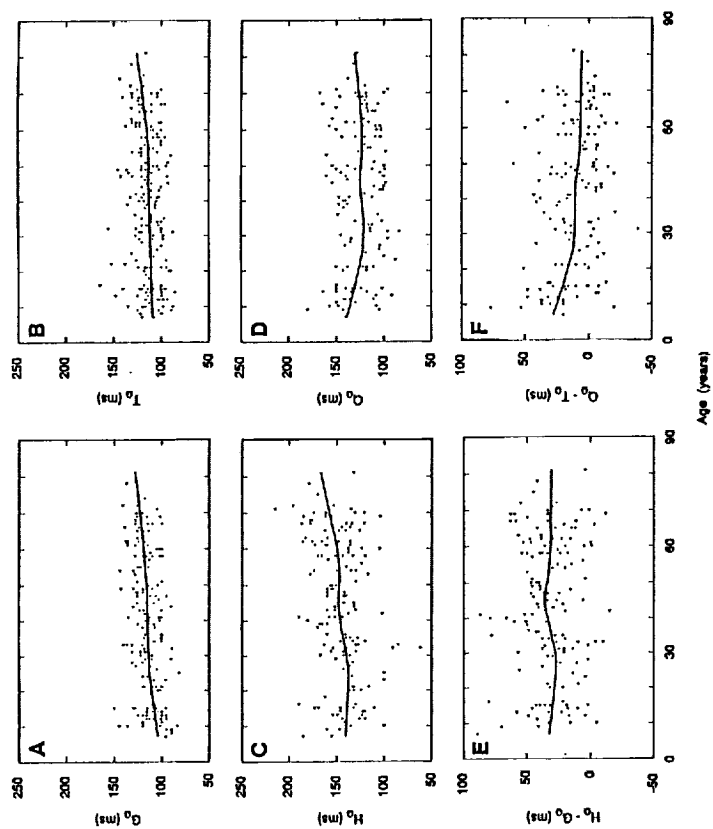


Figure 2

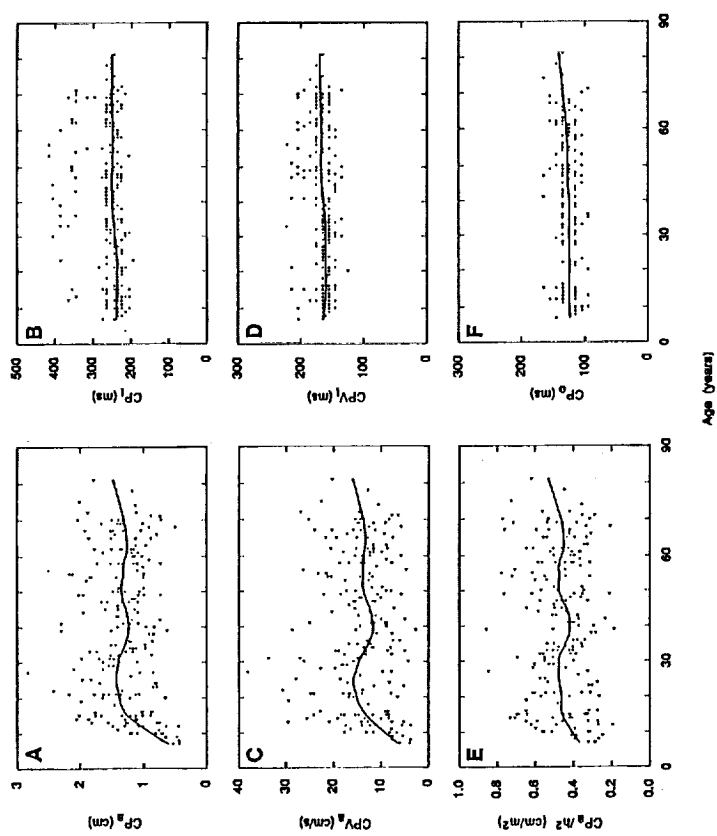


Figure 3