Neuromuscular Performance in a Kansas Mennonite Community: Age and Sex Effects in Performance

By Eric J. Devor,[1,2] Michael H. Crawford[2,3] and Wayne Osness[4]

ABSTRACT

The effects of age and sex on six neuromuscular performance traits are studied in a cross-sectional sample of 559 members of the Goessel, Kansas Mennonite community. Age and sex effects are assessed by stepwise polynomial regression which includes non-linear age terms up to the fourth power. Of the six traits studied only one, Hand Steadiness, fails to show a significant sex difference and only one, Trunk Flexibility, fails to show a significant non-linear trend with age. A general pattern, seen in these traits of accelerating performance decline after age 45 of up to 60%, is found to be consistent with that reported in other studies of the same traits. The consistency of this non-linear aging pattern suggests the presence of a general neuromuscular aging process. Moreover, this process appears likely to be related to a two-stage mechanism inferred from both animal and human studies involving a decline in protein synthesis and a loss of cell mass in nerve and muscle tissue.

Diminished ability with regard to muscular strength and neuromuscular performance associated with advancing age is an observation which seemingly has been well documented. Pioneering investigations by Quetelet (1835) revealed declines of 35 to 40% in the strength of various muscle groups in men between the ages of 25 and 60. Later in the 19th century, large studies guided by Galton showed a pattern of decline with age that was similar for several aspects of human physiology and neuromotor performance including grip strength (Ruger and Stoessiger, 1927; Elderton and Moul, 1928) and reaction time (Koga and Morant, 1923). Subsequent analyses of these phenomena have, however, been sporadic and have usually focused on only one or two aspects of human neuromuscular performance. The most extensively studied traits are muscular strength and stimulus-response characters such as reaction time. Rarely has a broad range of performance traits been investigated in a single population.

[1]Department of Psychiatry, Washington University School of Medicine and the Jewish Hospital of St. Louis, St. Louis, MO 63178.
[2]Laboratory of Biological Anthropology, University of Kansas, Lawrence, KS 66045.
[3]Department of Anthropology, University of Kansas, Lawrence, KS 66045.
[4]Department of Health, Physical Education and Recreation, University of Kansas, Lawrence, KS 66045.

Human Biology, May 1985, Vol. 57, No. 2, pp. 197-211.

In this paper we present the results from a study on the effects of age and sex on six neuromuscular performance traits. These traits represent a range of performance including strength, flexibility, neuromotor control, and response to external stimuli. Our results indicate that significant sex differences exist in five of the six traits and that significant age effects are present in all six. Moreover, the pattern of decline in performance with age is similar in all traits studied, regardless of sex. This result suggests that the process of aging impinges on the human neuromuscular system in a uniform manner.

Materials and Methods

Cross-sectional data on at least one of six neuromuscular performance traits were collected in the field from 559 members of the Alexanderwohl Mennonite congregation living in and around Goessel, Kansas (see Crawford and Rogers, 1982). The total sample was composed of 264 men, aged 15 to 96 years, and 295 women, aged 13 to 95 years. All subjects were voluntary participants in a University of Kansas study of aging and longevity. The age and sex distribution of these subjects, as well as basic physical characteristics, are presented in Table 1. As may be seen in this

Table 1

Sample Sizes by Sex and Age Cohort. Also Shown Are Average Physical Characteristics for Each Cohort

	Male			Female		
Age Cohort	n	Height[a]	Weight[b]	n	Height[a]	Weight[b]
15–24	25	1767.5 ± 73.6	78.7 ± 6.9	18	1658.9 ± 64.1	61.2 ± 10.2
25–34	35	1789.5 ± 87.3	78.3 ± 9.9	32	1655.1 ± 52.2	59.7 ± 6.9
35–44	25	1779.7 ± 56.1	81.6 ± 7.8	29	1640.3 ± 114.4	65.4 ± 12.1
45–54	37	1767.1 ± 65.9	88.1 ± 14.0	49	1638.6 ± 55.4	71.7 ± 14.4
55–64	44	1778.9 ± 47.7	79.1 ± 14.2	53	1639.3 ± 67.6	70.7 ± 12.4
65–74	55	1739.4 ± 64.9	79.6 ± 10.4	61	1593.6 ± 62.1	67.1 ± 11.7
75–84	34	1710.5 ± 78.3	73.3 ± 8.8	37	1571.0 ± 49.0	63.1 ± 11.3
85+	9	1690.0 ± 77.3	68.9 ± 9.5	16	1519.5 ± 17.0	58.7 ± 6.9
Total	264	1767.6 ± 67.3	79.5 ± 10.7	295	1617.7 ± 62.1	66.2 ± 11.4

[a]Height measured in millimeters.
[b]Weight measured in kilograms.

distribution, no subjects under the age of 15 were admitted (with the exception of a single 13 year old girl) and the majority of the sample (309/559 = 55.3%) was over the age of 55.

The six neuromuscular performance traits were chosen so as to provide a reasonable assessment of strength, body flexibility, and neuromotor function under the constraints that the task to be performed be relatively easy, especially for the elderly, and that the necessary testing equipment be portable. The six traits which met these criteria were:

1. Dominant Hand Strength, recorded as the maximum pressure (in kilograms) exerted by a subject on a Lafayette dynomometer with the preferred hand.

2. Hand Steadiness, measured electronically on a scale from 0 to 100. Each subject was required to hold the tip of a pencil-sized electric stylus inside each of three holes of decreasing size, which were cut 2.5 cm. apart in a metal plate 15 cm. wide. The first of these holes was 7 mm. in diameter, the second was 4 mm. in diameter, and the third hole was 2.5 mm. in diameter. A "hit" was recorded each time the stylus touched the side of a hole and the score for the trial was reduced from a maximum of 100.

3. Hand-Eye Coordination, measured electronically on a scale from 0 to 30. For this task each subject was required to follow a light moving counter-clockwise around a 2.5 cm. wide octagonal track using a 25 cm. long, L-shaped stylus. The "track" was a clear path in an otherwise opaque plexiglass surface approximately 35 cm, on a side. If the stylus left the clear path during pursuit a "hit" was recorded and the score reduced from a maximum of 30.

4. Simple Reaction Time, an electronically measured time (in milliseconds). A seated subject was required to respond to a visual (light) stimulus by moving the preferred hand from a resting position on a table to a point approximately 46 cm. forward and medial to the start position. The trial time started with the light flashing on and ended when the subject depressed a microswitch at the stop position. For this task each subject was given one untimed and three timed trials. The score used for this analysis was the fastest of the three time trials.

5. Movement Time, an electronically measured time (in milliseconds). This task is a self-initiated retest of the simple reaction-time task. The seated subject started the trial by moving the preferred hand from a second microswitch placed at the start position. Again, the required movement was approximately 46 cm. forward and medial to the start position. As before, one untimed and three timed trials were allowed and

the best time of the three timed trials was used. An examination of the pattern of simple reaction time and movement time trial times showed no significant habituation effect; that is, in neither trait was there a statistically significant tendency for any particular trial to be the fastest.

6. Trunk Flexibility, measured in centimeters. Each subject was required to sit on the floor in a straight-legged position with feet slightly apart. A wooden marker block on a measured slide was then placed between the legs of the subject and adjusted for individual height differences. The trial consisted of the subject pushing the block along the slide by means of outstretched arms, thus permitting the waist to be the only point of flexion. The maximum distance attained in a single, continuous motion was then recorded. This task proved to be the most difficult, as 58 (54.7%) of the 106 subjects over the age of 75 years were unable to perform the necessary motion.

Descriptive statistics, including means and standard deviations were computed on the raw data for the entire Mennonite sample as well as for sub-sets of the sample composed of males and females separately. In addition, means and standard deviations were computed for each of the sixteen age and sex cohorts shown in Table 1. Significance tests regarding sex differences in the mean and standard deviation were carried out for all six traits in all sub-sets using standard statistical techniques (cf., Snedecor and Cochran, 1980).

The direct effects of age and sex on performance were further assessed using a step-wise polynomial regression of the form,

$$\hat{y} = a + b_1x_1 + c_1x_2 + c_2x_2^2 + \ldots + c_nx_2^n + \epsilon \qquad (1)$$

where x_1 represents sex and x_2 represents age. Regressions of this type admit the possibility of non-linear age effects and, therefore, an acceleration of the decline in performance with age. In this analysis, non-linear terms up to fourth order ($n = 4$) were permitted. The final regression equations chosen contained only the significant ($p < 0.05$) terms.

Results

Observed means and associated standard deviations for all six neuromuscular performance traits are presented in Table 2, by total sample and by sex. The data in Table 2 indicate that only hand steadiness fails to exhibit a significant sex difference in mean performance level. Among the five remaining traits there is a wide range of magnitude in the observed sex differences, though all are statistically significant. The strongest mean

Table 2

Aggregate Descriptive Statistics (Mean ± S.D.) for the Six Neuromuscular Performance Traits in the Goessel Mennonite Community

Sex	Trait					
	DHS	HST	HEY	SRT	MT	TKF
Males	48.43 ± 13.35**†	80.18 ± 10.90	15.64 ± 4.81**	0.50 ± 0.11*	0.26 ± 0.11*	17.99 ± 9.84**
(n)	(161)	(257)	(259)	(252)	(252)	(237)
Females	30.03 ± 8.49	80.79 ± 10.83	13.41 ± 5.04	0.54 ± 0.11	0.31 ± 0.12	21.59 ± 9.82
(n)	(290)	(281)	(281)	(267)	(265)	(242)
Total	38.75 ± 14.38	80.50 ± 10.86	14.48 ± 5.05	0.52 ± 0.11	0.28 ± 0.12	19.90 ± 9.98
(n)	(551)	(538)	(540)	(519)	(517)	(479)

Significance of difference of male and female means: *$p < 0.05$, **$p < 0.01$.

Significance of difference of male and female standard deviation: †$p < 0.05$.

DHS = dominant hand strength, HST = hand steadiness, HEY = hand-eye coordination, SRT = simple reaction time, MT = movement time, and TKF = trunk flexibility.

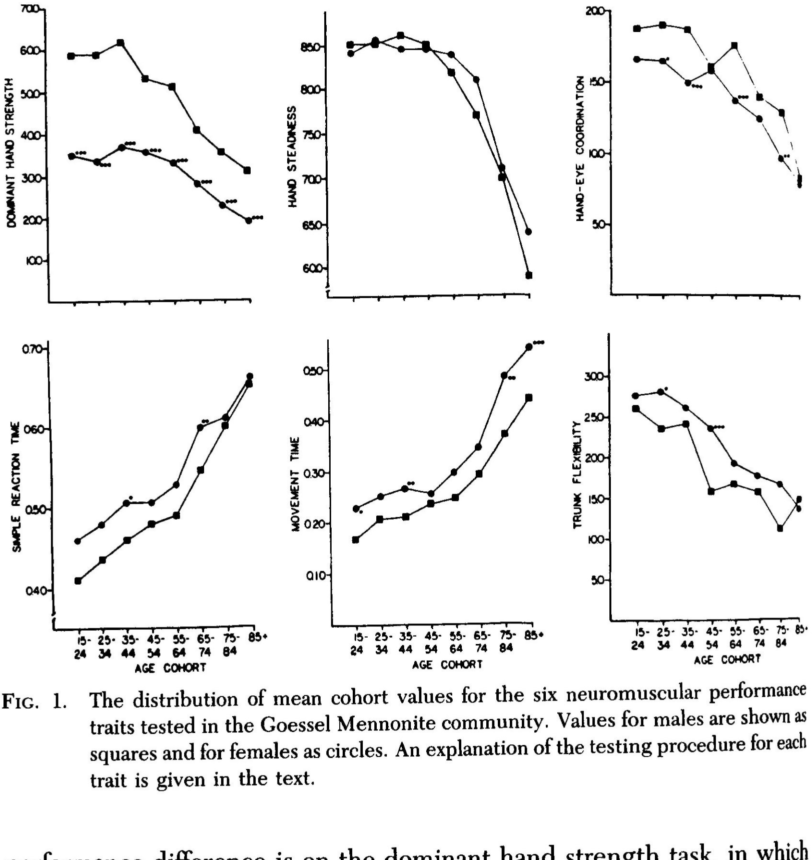

FIG. 1. The distribution of mean cohort values for the six neuromuscular performance traits tested in the Goessel Mennonite community. Values for males are shown as squares and for females as circles. An explanation of the testing procedure for each trait is given in the text.

performance difference is on the dominant hand strength task, in which males average a mean grip pressure more than one and one-half times greater than do females. In addition, it is only for dominant hand strength that there is a significant sex difference in the standard deviation. These results suggest that, while males are significantly stronger than females, they are also significantly more variable in their performance. On the other hand, females are significantly more flexible, as measured by trunk flexibility. Sex differences in mean performance on the stimulus-response traits, simple reaction time and movement times, are of lesser magnitude.

The patterns of differential performance by both sex and age cohort are shown for the six traits in Figure 1. Using ten year age cohorts, it can be seen that, with the exception of hand steadiness for which no sex differences in performance can be found, differential performance by sex persists throughout life. However, it is only for dominant hand strength that these differences are consistently significant. Overall, no age group shows a significant difference in performance for all six traits. The failure to observe a difference in performance in the aggregate hand steadiness data is made clear in Figure 1 as the age-cohort distributions of this trait are nearly indistinguishable. Finally, it should be noted that, excluding hand steadiness, males tend to perform better throughout life than do females in all traits except trunk flexibility.

With respect to age-specific performance independent of sex, there is a clear trend in all six traits shown toward diminished ability over time. Moreover, as evidenced by the best fit polynomial regression equations provided in Table 3, these declines in ability with age are, for the most part, significantly non-linear. Thus, except for trunk flexibility for which there are no higher order age terms, loss of ability with age appears to accelerate as individuals get older. The strongest of these effects is seen in hand steadiness where the only fourth order age term appears. The extreme cases are, therefore, hand steadiness, for which individuals remain relatively constant until the age of 55 and then decline very rapidly thereafter, and trunk flexibility, for which there is a constant loss of ability over time. An analysis of the six traits by sex showed that a significant difference in the regressions is obtained only for dominant hand strength. Loss of grip strength in males, over time, was best fit by a quadradic function of age, whereas for females, the best fit was by a cubic function of age ($DHS_m = 64.4 - 0.005\ (Age^2)$ versus $DHS_f - 37.2 - 0.288 \times 10^{-4}\ (Age^3)$, $p < 0.01$). However, this difference appears to be only statistical, given the pattern seen in Figure 1. No similar differences were observed in the other five traits.

Another consistent finding in these data is shown in Figure 2. Each interval represents a decline of 20% from maximum performance. Note that the data for simple reaction time and movement time are given as the complements of the actual mean scores. This is done in order to more clearly show the similarity in the cross-sectional performance pattern by age cohort as can be seen, the proportionate decline in ability from the maximum level by age 85 is roughly the same for a trait regardless of the sex or the speed with which it progresses. For example, while there is a significant difference in dominant hand strength with respect to sex-specific mean performance, variation of performance, and rate of loss in ability, the result is the same in the end. Both males and females experience a loss of hand strength of about one-half by the ninth decade (49.8% in men and 48.5% in women). A similar loss of ability is seen of hand-eye

Table 3

Best Fit Polynomial Regression Equations for the Six Neuromuscular Performance Traits in the Goessel Mennonite Community

Trait	Best Fit Polynomial*	R^2	F(df)
DHS	$72.478 - 17.374\ (\text{Sex}) + 0.222\ (\text{Age}) - 0.006\ (\text{Age}^2)$	0.683	392.875 (3,548)
HST	$82.490 + 0.114\ (\text{Age}) - 0.531 \times 10^{-6}\ (\text{Age}^4)$	0.353	142.423 (2,536)
HEY	$20.974 - 2.060\ (\text{Sex}) - 0.982 \times 10^{-3}\ (\text{Age}^2)$	0.208	70,307 (2,538)
SRT	$0.352 + 0.043\ (\text{Sex}) + 0.323 \times 10^{-4}\ (\text{Age}^2)$	0.333	125.659 (2,517)
MT	$0.122 + 0.052\ (\text{Sex}) + 0.389 \times 10^{-6}\ (\text{Age}^3)$	0.350	136,422 (2,515)
TKF	$26.182 + 3.921\ (\text{Sex}) - 0.235\ (\text{Age})$	0.211	60,322 (2,477)

*Includes only terms significant at $\alpha = 0.05$.

DHS = dominant hand strength, HST = hand steadiness, HEY = hand-eye coordination, SRT = simple reaction time, MT = movement time, and TKF = trunk flexibility.

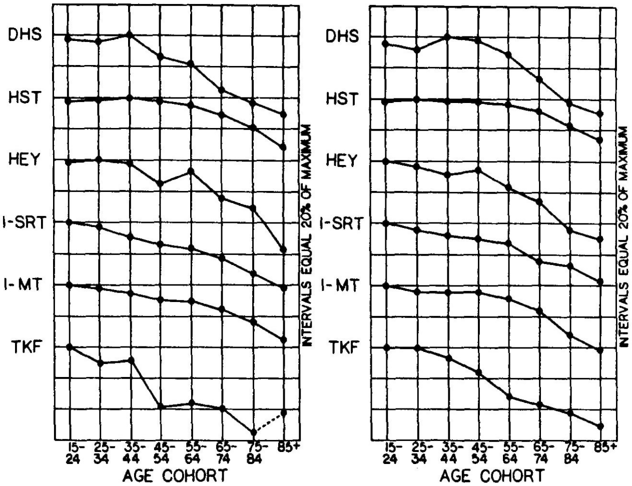

FIG. 2. Proportionate declines in mean cohort performance for the six neuromuscular performance traits tested in the Goessel Mennonite community. Data for males is presented on the left and data for females is presented on the right. Data on simple reaction time and movement time are presented here as (1x̄), see text for explanation. DHS = dominant hand strength, HST = hand steadiness, HEY = hand-eye coordination, SRT = simple reaction time, MT = movement time, and TKF = trunk flexibility.

coordination (56.1% in men and 51.5% in women). However, in hand steadiness the most rapid decline with age is associated with the smallest proportionate loss in ability of the six traits (32.2% in men and 25.6% in women). Conversely, the most steady decline with age, seen in trunk flexibility, is associated with the largest proportionate losses of ability (59.1% in men and 59.0% in women). Note that the figure for males is an estimate based upon extrapolating from the value observed in the 75-84 age group. Combining the proportionate losses for all six traits gives an overall average decline in neuromuscular performance of 43.2%, the majority of which occurs after the age of 55.

Discussion

An analysis of the effects of age and sex upon neuromuscular performance has been carried out. In general, neuromuscular function in man appears to decline with age in a non-linear manner. Early in adulthood neuromotor performance remains relatively constant, but begins to decline after the fifth decade. This loss of ability accelerates as the individual ages and results in an average loss of 43% of maximum adult performance level by the ninth decade. Significant sex differences in mean performance are seen for all traits except hand steadiness. However, the overall proportionate loss of ability by the ninth decade is the same for any one trait regardless of sex. Thus, based upon these data, it appears that men and women perform differently throughout life, but experience a similar aging process.

The patterns of aging in performance shown here are consistent with those shown in many other investigations. In a classic study of muscular strength, Quetelet (1835) demonstrated that hand strength in men reached its maximum near the end of the third decade, but declined by 37.5% by the end of the sixth decade. Moreover, the loss in strength over time was clearly non-linear being approximately 8.0% at the fourth decade and 20.0% at the fifth decade. In the studies by Galton in the 1880's, grip strength was seen to reach its highest level early in the third decade both in men (Ruger and Stoessiger, 1927) and in women (Elderton and Moul, 1928). Following age 30, grip strength was shown to lessen slowly at first and then to accelerate to the point where there was a 33.0% loss in ability by age 80 in men and 23.0% loss in ability by age 70 in women. In addition, men were seen to perform better than women throughout life. This pattern of aging in performance, as measured by muscular strength is repeated over and over again. Ufland (1935) and Burke et al. (1953) both report a maximum grip strength in the third decade and a curvilinear decline thereafter resulting in an overall loss of 35.1% by age 69 and 35.6% by age 79 respectively.

Our observations on simple reaction time and movement time also follow this classic aging pattern with declines in ability measured by slowed response times of 37.4% and 41.7% in the former among males and females respectively, and of 34.9% and 40.6% in the latter among males and females respectively. One of the earliest studies of aging in response time was also conducted in the last century by Galton. The data obtained indicated that minimum reaction times were achieved by subjects early in the third decade of life (Koga and Morant, 1923). Further, the authors commented that the subsequent loss of ability was demonstrably non-linear with an end result of a decline of 14.6% by age 81.5. An investigation by Bellis (1933), which was one of the few early studies of reaction time to include women, showed that response to a visual stimulus was consistantly slower in women than in men, but that both sexes displayed minimum times in the third decade. The subsequent decline in ability was, however, proportionately the same with men dropping by 42.1% by age 59 and women by 40.9% by the same age. This finding was replicated by Hodgkins (1963) who reported the same consistent sex difference in response speed and, again, a curvilinear diminution of function resulting in a loss of 44.3% in men by age 80 and 37.8% in women by age 80. The classic study in which both simple reaction time and movement time were examined was reported by Pierson and Montoye (1958). Their study of 400 male subjects showed that both measures peaked by age 20 and declined thereafter. The increase in response speed was less severe in simple reaction time, 24.2% by age 80, than in movement time, 48.5% by age 80. The consistency of these results from several groups and with varying experimental designs prompted Birren et al. (1980, p. 294) to comment that, "this general finding has been replicated many times—to the point where slowing in simple reaction time with age is, perhaps, one of the most replicated findings of behavioral change with age." In addition, though there is a range of proportionate increases in reaction speed due to different testing procedures, Welford (1977, p. 463) notes that, "Of the studies done since 1958, the median percentage increases of reaction time from the twenties to the sixties has been about 26."

While muscular strength and reaction speed traits have been the most extensively studied, our results on hand steadiness, hand-eye coordination, and trunk flexibility along with those of the few investigators who have examined similar traits suggest that the pattern of aging revealed is generalizable to the entire human neuromotor system. Ruch (1934) showed that the maximum scores attained on a rotary pursuit experiment similar to our hand-eye coordination task were by subjects in their twenties and that the decline in scores by older subjects was 2.0% in the 34-59 age group and 16.3% in the 60-86 age group. An investigation of manual motility by Miles (1931) revealed a peak performance at age 18 and a curvilinear decline of 58.6% by age 80. Miles notes that the age-specific pattern of scores on that test were nearly identical to those obtained for a simple reaction time test. Also, while most measures of flexibility are made in degrees (Salter, 1955), studies of the effects of aging on flexibility produce results similar to those obtained here. For example, Wessel et al. (1963) showed that flexibility, as measured by the sum of five joint movements, in a sample of 50 women aged 29 to 69 years peaked in the 30-34 age group and then declined erratically over the next 35 years. However, as with our data, no significant curvilinear trend could be seen. Loss of flexibility with age is well known and several studies have cited it as a consistent finding in the aged (Shephard, 1978),

On the basis of the present data and numerous comparative studies of aging in the human neuromuscular system, it seems clear that there is a general aging phenomenon in which neuromotor function peaks early in adulthood following which deficits in function begin to accumulate as individuals age. Among those who have focused on stimulus-response traits such as simple reaction time, there is some disagreement as to the nature of the age specific decline in ability. Arenberg (1980), for example, cites CNS structural impairment as the root cause of loss of function. As more and more of the CNS becomes impaired, individuals find it increasingly difficult to process input. However, several investigators including Gottsdanker (1982) suggest that the cause is to be found in faulty neuromotor control processes in the peripheral nervous system. In order to address this question we followed the model of total simple reaction time presented by Spirduso (1980) by regarding movement time as the motor control component such that the difference SRT $-$ MT $= \Delta_T$ represented the CNS processing component (Crawford et al. 1984). We found that the age-specific change in simple reaction time was followed closely by changes in movement time ($r = 0.749$) but that there was no relationship between Δ_T and age. We concluded, based upon this simple additive model, that the age-specific increase in simple reaction time was due to faulty neuromotor control processes rather than to CNS impairment.

Support for this interpretation may be found in the original Galton data from the last century. Both Ruger and Stoessiger (1927) and Elderton and Moul (1928) present age-specific distributions of tests of sensory acuity, vision and hearing. Both studies report dramatic losses in visual acuity of 81.0% in males and 77.0% in females and in hearing of 33.0% in males and 29.0% in females. More important, however, are the shapes of these age-specific distributions. Visual acuity peaks both in men and women near the end of the second decade and falls off very slowly until the middle of the fifth decade. After age 45 there is a very rapid fall off which, in men, is nearly perpendicular. By the middle of the sixth decade nearly all of the proportionate loss observed by age 80 has already occurred. Auditory acuity, on the other hand, shows a much more linear decline with age. If CNS processing were at the root of age-specific declines in neuromotor ability, such functions as sight and hearing should map more closely not only with each other, but the neuromuscular functions as well. However, the patterns observed for auditory and visual acuity in men and women bear little resemblance to one another, nor to those for muscular strength or, more importantly, for reaction times to visual and auditory stimuli (Koga and Morant, 1923).

If we are to accept the proposition that loss of neuromuscular ability with age is due to a general phenomenon affecting neuromotor control processes, there must be a mechanism whose decay is common to these control processes. Norris et al. (1953) demonstrated that the conduction velocity (M/sec.) of human motor nerves is at its highest among individuals aged 20-39 years, but that there is a steady decline to a proportionate loss of 17.5% by the ninth decade. Moreover, this decline is slightly curvilinear yet it is insufficient to account for the patterns observed in the neuromuscular system. Gutmann and Hanzlíková (1972) support this finding, but add (p. 156) that, "the main old-age disturbance in nerve- and muscle-cells will be reflected by a shift in balance between processes of synthesis and breakdown of proteins, and this shift will progressively result in old age atrophy and involution." Studies of human nerve and muscle cells and of various animal models indicate the existence of a two-fold mechanism (Gutmann and Hanzlíková, 1972). First, there is a significant decrease in cellular RNA and in RNA precursor uptake in aging cells reflecting a decline in protein synthesis. Second, there is a decrease in tissue DNA reflecting a loss of cell mass. This process, occurring in both nerve and muscle cells, would be sufficient to produce the cumulative age effects observed in the entire neuromuscular system.

Finally, given that a general physiological process may exist which explains the age-specific pattern of human neuromuscular performance, the question arises as to its inevitability. Spirduso (1980) reviewed several studies which demonstrated that physical activity significantly slows the age-specific declines in ability. In addition, there are animal studies indicating that transmittor synthesis, muscle contraction speed, and muscle mass do not change nearly so rapidly in regions of the body under constant stimulation throughout life such as in the diaphram and respiratory musculature (Spirduso, 1980). Thus, while aging in the neuromuscular system may be inevitable, the process is responsive to intervention.

Acknowledgements

We wish to express our appreciation to the members of the Goessel, Kansas Mennonite congregation without whose cooperation and good will this project would not have been possible. We also thank the anonymous reviewers for their many helpful suggestions. This work was supported by NIH Grant AG01646-01 and by NIMH Postdoctoral Training Grant MH-14677.

Received: 20 June 1984; revision received: 11 October 1984.

Literature Cited

Arenberg, D. 1980 Comments on processed that account for memory decline with age. *In*: L. W. Poon, J. L. Fozard, L. S. Cermak, D. Arenberg and L. W. Thompson (eds.) New Directions in Memory and aging. Laurence Erlbaum, Hillsdale, N.J.

Bellis, C. J. 1933 Reaction time and chronological age. Proc. Soc. Exper. Biol. Med. **30**: 801.

Birren, J., A. M. Woods and M. V. Williams 1980 Behavioral slowing with age: Causes, organization, and consequences. *In*: L. W. Poon (ed.) Aging in the 1980's: Psychological Issues. American Psychological Association, Washington, D.C., pp. 293-308.

Burke, W. E., W. W. Tuttle, C. W. Thompson, C. D. Janney and R. J. Weber 1953 The relations of grip strength and grip strength endurance to age. J. Appl. Physiol. **5**: 628-630.

Crawford, M. H. and L. Rogers 1982 Population genetic models in the study of aging and longevity in a Mennonite community. Soc. Sci. Med. **16**: 149-153.

Crawford, M. H., E. J. Devor and W. Osness 1984 Age and simple reaction time: relations between neural and motor components. J. Gerontol. (submitted).

Elderton, E. M. and M. Moul 1928 On the growth curves of certain characters in women and the inter-relationships of these characters. Ann. Eugen. **3**: 277-336.

Gottsdanker, R. 1982 Age and simple reaction time. J. Gerontol. **37**: 342-348.

Gutmann, E. and V. Hanzlífková 1972 Age changes in the neuromuscular system. Scientechnica Ltd., Bristol.

Hodgkins, J. 1963 Reaction time and speed of movement in males and females of various ages. Res. Quart. **34**: 335-343.

Koga, Y. and G. M. Morant 1923 On the degree of association between reaction times in the case of different senses. Biometrika, **15**: 346-372.

Miles, W. R. 1931 Measures of certain human abilities throughout the life span. Proc. Nat. Acad. Sci. **17**: 627-633.

Norris, A. H., N. W. Shock and I. H. Wagman 1953 Age changes in the maximum conduction velocity of motor fibers of human ulnar nerves. J. Appl. Physiol. **5**: 589-593.

Pierson, W. R. and H. J. Montoye 1958 Movement time, reaction time, and age. J. Gerontol. **13**: 418-421.

Quetlet, A. 1835 Sur l'homme et le développement de ses facultés. Bochelier, Paris.

Ruch, F. L. 1934 The differentiative effects of age upon human learning. J. Genet. Psychol. **11**: 261-286.

Ruger, H. A. and B. Stoessiger 1927 On the growth curves of certain characters in man (males). Ann. Eugen. **2**: 76-110.

Salter, N. 1955 Methods of measurement of muscle and joint function. J. Bone Joint Surg. **37B**: 474-491.

Shephard, R. J. 1978 Physical activity and aging. Croon Helm Ltd., London.

Snedecor, G. W. and W. G. Cochran 1980 Statistical methods, 7th ed. Iowa State University Press, Ames.

Spirduso, W. W. 1980 Physical fitness, aging and psychomotor speed: A review. J. Gerontol. **35**: 850-865.

Ufland, J. M. 1935 Einfluss de Lebensalters, Geschlechts, der Konstitution und des Berufs auf die kraftverschieder Muskelgruppen. Arbeitsphysiol. **6**: 653-663.

WELFORD, A. T. 1977 Causes of slowing with performance in aging. *In*: H. P. Von Hahn (ed.) Interdisciplinary topics in Gerontology, **11**: 43-51.

WESSELL, J. A., A. UFER, W. D. VAN HUSS AND D. CEDERQUIST 1963 Age trends of various components of body composition and functional characteristics in women aged 20-69 years. Ann. N. Y. Acad. Sci. **110**: 608-622.