Reduction in
Sensorimotor Control With Age

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This article reviews declines in motor performance associated with aging. The data are specifically categorized into subsections to facilitate the formation of hypotheses that may be tested by specific intervention and rehabilitation programs. It is no longer acceptable for investigators to think of age-related declines in sensorimotor control as a unitary deficit. Data are reviewed that suggest that the elderly have a reduced capability to use advanced preparatory information, a difficulty in processing stimuli, an inability to regulate movement speed, and an inability to adequately calibrate afferent information. Each of these deficits may be caused by a specific reduction in sensorimotor processing. It is important that future research addresses the loci of the movement slowing and increased movement variability that are so prevalent with aging. With this knowledge, intervention programs may be able to minimize or reverse the effects of aging on motor control more realistically.

Now more than ever, people are living beyond age 65. Thus, it is not surprising that in the last decade there has been increased interest in the relationship between motor control and coordination and fitness, particularly in older adults. With advanced age comes a decline in motor control and motor functioning (Cerella, 1985; Larsson, 1982; Mortimer, Pirozzolo, & Maletta, 1982; Sheldon, 1963; Spirduso, 1982; Welford, 1977, 1984; Woollacott, Shumway-Cook, & Nashner, 1982). The causes of these declines in motor functioning are not known but are presumed to be related to physiological changes such as decreased bone mass and a reduced number of central and peripheral nerve fibers (Black, 1979; Kenshalo, 1977; Scheibel, 1979; Welford, 1982). However, the underlying mechanisms leading to these changes are not well understood, as they have been difficult to both discover and isolate. Without specific knowledge of such deficits, efforts to introduce exercise interventions directed toward maintaining and/or regaining motor performance in the elderly are likely to be ill-founded.

The majority of the literature on movement slowing and increased inaccuracy with advancing age suggests that these deficits may be due to an alteration in movement control processes. From neuropsychological studies that have used older adults there are findings showing (a) a failure to use advance preparatory information (Botwinick, 1965; Gottsdanker, 1982, 1984); (b) a difficulty in processing stimuli,
as well as making responses that are spatially incompatible (Rabbitt, 1979); and (c) an inability to regulate performance speed, resulting in increased time to execute tasks requiring precision (Rabbitt, 1979; Salthouse, 1979; Salthouse & Somberg, 1982).

The intent of this review is to describe the types of sensorimotor deficits in the elderly that are known so that future targeted exercise intervention studies can focus on realistic hypotheses. As there are several aspects of motor performance that decline with advanced aging, it is no longer acceptable to think of a unitary cause (Salthouse, 1979). In this article, we will focus specifically on recent data that show changes in kinematics of arm movements, prehension tasks, and handwriting that are beginning to reveal why movement becomes slower and less accurate in older adults.

**Movement Duration: A General Slowing**

It is well established that the elderly show a pronounced slowing of movement (for a review see Diggles-Buckles, 1993). Contributions to this slowing include a failure of the elderly to fully preprogram movements and an increased emphasis on accuracy at the expense of movement speed. The results of these studies are consistent: In a variety of situations older adults exhibit longer reaction times than younger adults.

As observed from reaction-time experiments, the elderly appear unable to fully program movement patterns before the onset of movement. This is particularly evident when older adults are required to maintain a movement preparation (Amrhein, Stelmach, & Goggin, 1991) or to restructure movement plans as a result of receiving an invalid precue (Stelmach, Goggin, & Amrhein, 1988). When required to restructure the parameter of movement extent, the elderly show a decrease in reaction time (RT) but an increase in movement time (MT) compared to when they are required to restructure an arm, direction, or a combination of such parameters. In contrast to strategies employed by young adults, these data suggest that the restructuring of the prepared parameters occurs during movement execution and not during the programming phase. Performing these modifications on-line rather than before the movement begins appears to contribute to increases in total movement duration.

An additional contribution to the increase in movement duration for the elderly is related to the observation that the elderly have slower response latencies when preparing shorter rather than longer movements (Stelmach, Amrhein, & Goggin, 1988; Stelmach, Goggin, et al., 1988). This implies that, in contrast to younger adults, the elderly control movements that have extended amplitudes in a closed-loop manner rather than through the use of a prespecified movement plan. Due to the temporal constraints caused by detection and correction processes, reliance on feedback information mandates increased slowing of the movement being executed.

Several papers have documented that discrete movement durations are an approximately linear function of the index of difficulty (Fitts, 1954) for both young and older adults, with the older participants yielding a steeper slope (Brogmus, 1991; York & Briederman, 1990). Data that show such relationships imply that the performance of older adults is an approximately linear increasing function of the performance of the young. While this relationship is not completely understood, it is likely that the elderly, when executing movements with large indexes of difficulty,
show pronounced lengthening in the deceleration phase of the movement. Such a disproportional decline in performance suggests that aging does not impact all cognitive-motor processes equally (Salthouse, 1979).

**Changes in Movement Trajectories and Force Control**

In addition to the general slowing in movement speed, the elderly often show different execution patterns for arm movements, prehensile actions, and handwriting in comparison to young people. In contrast to the reaction time and movement time findings, results involving functional tasks are much less straightforward. Nevertheless, it appears from these data that the elderly have difficulty in adequately specifying the impulses that control the movement trajectories.

**Arm Movements**

Newer technology that allows the quantification of movement kinematics can potentially lead to explanations of how movements made by the elderly differ from those made by the young (Warabi, Noda, & Kuto, 1986; Welford, Norris, & Shock, 1969). The kinematics of aiming movements can be divided into two portions: an acceleration phase before peak velocity is reached and a deceleration phase after peak velocity. The deceleration phase is seen as a “homing in” on the target. Variability arising during the acceleration phase of the movement remains constant or even decreases during the deceleration phase. Kinematic differences between elderly and young participants can be seen in the performance of elbow flexion and extension movements to control a manipulandum that positions a cursor at different target locations (Cooke, Brown, & Cunningham, 1989). While the young participants perform movements with symmetrical, bell-shaped velocity profiles, the elderly spend a greater proportion of the movement in the deceleration phase.

Such findings have been confirmed in other arm aiming studies (Haaland, Harrington, & Grice, 1993; Darling, Cooke, & Brown, 1989; Stelmach, Goggin, et al., 1988). This increase in deceleration time contributes to the increase in total movement duration. The acceleration phase is assumed to be under open-loop control with no need for feedback information. The deceleration phase, however, is under closed-loop control and uses error detection and correction information from both motor and sensory systems. Since the deceleration phase of movement is primarily lengthened, this deficit may depend on the ability of the elderly to coordinate sensory and motor processes. Removal of visual feedback during the movement reveals that the elderly may have a stronger dependency on visual information (Haaland et al., 1993). When visual feedback is removed, the variability of the deceleration phase is increased for both young and elderly adults; however, the effect is more substantial for the elderly.

Antagonist muscle activity produced during the deceleration phase is thought to be important to correct for the variations created during the acceleration phase of arm movements (Darling et al., 1989). However, Darling et al. (1989) observed that, although the elderly do show normal bursts of agonist activity, they occasionally exhibit antagonist bursts that are often premature, resulting in coactivation. The authors suggested that this coactivation may reduce point-to-point movement variability by increasing joint stiffness and viscosity. This coactivation strategy is vastly different from the precisely timed alternating phases of agonist and antagonist activity employed by the young.
Changes in the ratio of peak velocity to mean velocity with changing movement amplitude also differs between young and elderly adults (Cooke et al., 1989). This ratio typically remains fairly constant with increasing movement duration for young participants. Such data suggest that the movement pattern remains invariant and is rescaled for movements of differing amplitudes. When performing elbow flexion and extension of varying amplitudes, elderly participants in Cooke et al.’s (1989) study showed great variation in this ratio, with the highest ratio values exhibited for smaller amplitude values. The fact that the ratio was more variable for elderly participants suggests that the amplitude of their movements cannot be changed by simply rescaling the initial impulses.

Complexity of the task is another factor that is related to the performance of arm movements in the elderly. Stelmach et al. (1988) explored differences between young and old adults performing unimanual and bimanual symmetric and asymmetric arm movements of varying amplitudes. The bimanual asymmetric task required individuals to reach for targets placed at different amplitudes with each arm. As expected, the elderly moved slower in all cases. They were also incapable of making trajectory adjustments during the execution of the movement, leading to a more asynchronous finish. These findings suggest that the elderly lose some of the ability to regulate movements via on-line feedback during movement execution.

**Prehensile Actions**

In recent years, research on older adults has increasingly emphasized tasks involved in daily living. The appeal of such functional tasks is that they stress goal-oriented behavior and are highly practiced. Thus, the data obtained provide a better approximation of how aging affects sensorimotor performance.

**Reach to Grasp Movements.** Prehension research paradigms require individuals to reach and grasp objects using either a whole hand grip (thumb opposite all fingers) for large objects or a precision grip (thumb opposite the index finger) for smaller objects. Kinematics of both the transport action and the grip aperture can be measured. Bennet and Castiello (1994) found that, similar to the kinematics of arm aiming movements, the elderly spend a greater amount of time in the deceleration phase of prehension tasks, regardless of the type of grip employed. Coordination of transport and manipulation components in prehension tasks can be examined by correlations between different characteristics of wrist transport and grip aperture such as time of peak acceleration of the wrist and time of maximum grip aperture. Bennett and Castiello observed these correlations to be higher for younger adults than for the elderly. Thus, there is some evidence of a breakdown in coordination for the elderly.

Besides general slowing, Chaiken (1992) also found longer deceleration times for the elderly during prehension, but found no impairment in coordination of the transport and reach components. When expressed as a percentage of movement duration, however, maximum grip aperture occurred earlier for the elderly. Such data imply that the elderly rely to a greater extent on on-line feedback, suggesting perhaps a greater emphasis on accuracy. This is further supported by Chaiken’s observation that some of the elderly participants slightly closed and then reopened the grip aperture twice during wrist transport. This suggests greater reliance by the elderly on visual feedback and is consistent with Haaland et al.’s (1993) finding that removal of visual feedback had more of a detrimental effect on the elderly than on the young.
Precision Grip. Not all motor skills infer reduced force control with aging. It appears from Cole (1991) that the elderly use grip forces that are in excess of twice that of young participants when lifting small objects. These high forces were well above the slip forces required for the objects (measured as the force at which the object begins to slip from grasp). The intertrial variability was higher for the elderly participants, leading Cole and Beck (1994) to further this study to determine if intrat trial variability of force control played a role in the high grasp forces employed by elderly participants. There were no differences observed in variability of force control between the elderly and the young participants. Perhaps variability of force control does not affect this movement because it is controlled and coordinated by many muscles. The impairment observed appears to be an inability to calibrate afferent information such as tactile sensitivity. The overproduction of force observed undoubtedly impairs the elderly’s ability to perform a variety of hand functions requiring dexterity and fine motor control.

Although Cole and Beck (1994) did not observe greater variability of force output for elderly participants performing a multi-muscle task, increased variability in force control for the elderly has been demonstrated (Galganski, Fuglevand, & Enoka, 1993). Older adults have shown greater force variability, even when expressed relative to the target force, in performance of isometric abduction of the index finger. These variations were greater at lower force levels. This variability may not have been seen in the grasp studies because the precision grip used requires coordination of many small muscles. Control of several muscles allows for compensation of variability.

Handwriting Tasks

Handwriting is a highly complex motor skill, requiring coordination of the timing of movements by the fingers, wrist, and arm in many combinations to create individual strokes (Norman, 1980). The small, rapid movements used are primarily controlled by ballistic muscle contractions and are not affected by inertial, frictional, or gravitational forces (Teulings, 1988). These small amplitude movements do not require an excessive range of motion or high forces. Having participants write on a digitizing pad allows the quantification of stroke characteristics such as size, duration, and acceleration.

Teulings and Stelmach (1993) found differences in handwriting production between young and elderly individuals for writing the stroke sequence ellehell. As seen in Figure 1, the elderly maintain accuracy of stroke size, but show reductions in peak accelerations and stroke durations. These declines suggest that the elderly may not be able to produce adequate forces to control normal handwriting. However, as the necessary forces are quite small, it is not likely that the deficit lies in the inability to produce the appropriate force levels.

Handwriting investigations have shown that movement slowing for the elderly is related to task complexity. Dixon, Kurzman, and Friesen (1993) investigated differences in handwriting performance for familiar and unfamiliar tasks. The familiar tasks included copying the letter h and sentence and text copying. The unfamiliar tasks included copying the letter h backwards and grapheme copying. In all cases the young participants were faster than the elderly. These age differences were magnified for unfamiliar but attenuated for familiar tasks.

Based on these articles, it can be seen that while elderly adults execute movements similarly to younger adults, there are some fundamental differences. The
The accuracy (signal-to-noise ratio or SNR) of stroke sizes, peak accelerations (force), and stroke durations in young (Y) and elderly (E) handwriting (N = 6).

**Figure 1** — The accuracy (signal-to-noise ratio or SNR) of stroke sizes, peak accelerations (force), and stroke durations in young (Y) and elderly (E) handwriting (N = 6).


The elderly show an overreliance on feedback control, evidenced by longer deceleration phases of movement and difficulties arising when visual feedback is withdrawn. Inabilities to produce adequate force levels are seen in handwriting and reaching tasks, while an overproduction of force occurs in precision grip tasks due to the reduced afferent input from the fingers. These data suggest that the elderly place a greater reliance on feedback control and have a reduced ability to interpret required sensory information.

**Can Practice Mitigate Sensorimotor Declines?**

The fact that elderly adults perform worse on unfamiliar compared to familiar tasks raises the possibility that the observed age differences are not fundamental limitations of the motor system. These limitations should be thought of as transitory effects rather than as primary deficits if practice can reduce or eliminate the observed age differences. Indeed, with practice the elderly have been shown to decrease movement time faster than young adults on handwriting tasks (Dixon et al., 1993). However, this effect appears to be task-dependent. Spirduso and Choi’s (1993) elderly and young participants became more accurate at a triangle tracing task that utilized opposition forces between the thumb and index finger over three days of practice. The elderly participants improved more than the young from Day 1 to Day 2, but then their performance stabilized by Day 3. The young participants, however, improved in a linear fashion across all 3 days. Thus, the elderly improved faster than the young on the unfamiliar handwriting tasks, but their net improvement on the triangle tracing task was less than that seen in the younger participants. Jagacinski, Greenberg, Liao, and Wang (1993) investigated whether motor skill learning could be enhanced with auditory cues. The auditory cues actually aided performance on a rhythmic tracing task more for the elderly than for young adults; however, even after many practice trials, the elderly still did not perform as well as the young.
It appears that practice can improve performance for the elderly, with the amount depending on the task. In almost all cases, though, performance levels fail to reach those of younger adults, even following substantial practice. This suggests that the deficits in sensorimotor processes represent a reduced capacity for performance and reflect fundamental limitations in motor control. However, even a partial restoration of functional capacity, as seen with practice, can increase the quality of life.

**Concluding Comment**

It should be apparent from the literature covered that research is beginning to determine why there is pronounced slowing in the movement execution of the elderly (Cole & Beck, 1994; Haaland et al., 1993; Teulings & Stelmach, 1993). Most of this research goes beyond surface descriptions and seeks to provide a detailed analysis of how the movement parameterization processes are impaired with advanced age. The burden of further research on the manifestations of aging, however, is to explain the locus of the slowing and the increased variability of movement, which is so reliably observed in the elderly. As these accounts of the motor physiology become more lucid, targeted intervention studies that use physical activity become more plausible.

Future research, where physical activity interventions are contemplated, must deal with the methodological challenge that comes from speed/accuracy tradeoff relationships seen in aging research. Regardless of whether the research is investigating improvements due to exercise within subjects or between subject groups, the design should address whether young and elderly participants are operating on different parts of the speed/accuracy curve. It is well documented that with advancing age, speed is reduced to maintain accuracy (Diggles-Buckles, 1993; Welford et al., 1969). This occurs in many tasks, including grasping, reaching, and handwriting, where the speed is self-controlled. Often, improvement of performance on these tasks is measured by both accuracy and speed of response. However, there is a point beyond which further increases in speed are accompanied by a concomitant decrease in accuracy. The problem associated with this phenomenon appears when participants are instructed to “respond as rapidly and accurately as possible.” This vagueness leaves much room for interpretation; some participants will place more emphasis on accuracy, others on speed. Recognition of this phenomenon suggests that participants should be tested at differing levels of speed and accuracy to determine where along the speed–accuracy curve their performance lies. The introduction of such experimental designs will aid interpretation of comparisons made between age groups, exercise and control groups, and/or pre- and postintervention groups.

**References**


Acknowledgment

The preparation of this paper was supported in part from NIH grant NS17421-09 awarded to G.E. Stelmach.