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Age-related differences in performance of stereotype arm movements: movement and posture interaction

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Abstract. Postural destabilizations in response to cyclic pull-and-push arm movements were compared in young and elderly subjects, with the goal of determining how age-related differences in postural stability influence strategies of cyclic arm movements made at different speeds, against different loads and while standing on support surfaces of different compliances. The results show that elderly subjects performed the experimental task more slowly with a lower mean movement frequency and a smaller amplitude. Despite of this fact, the elderly's upright posture was destabilized by this movement to a greater extent than in young subjects. The older adults exhibited lower damping of the disturbing torques produced by arm movements as evidenced by a higher amplitude of the center of foot pressure excursions. The results document close reciprocal motor and posture interaction and indicate that parameters of the voluntary movement task such as cyclic arm movements might be used as a sensitive measure of postural stability.

INTRODUCTION

Two major components can be distinguished in every motor task: goal oriented movements - the action, and postural components - compensation for the reaction produced by the action (Hess 1943, Massion 1992). Thus, the neural specification for movement requires the planning of the intended movement and also the anticipating of the mechanical and sensory consequences of the task so that appropriate postural corrections can be made while the task is being executed (Belenkiy et al. 1967, Lee 1980, Cordo and Nashner 1982, Friedli et al. 1984, 1988, Massion and Dufosse 1988). As both of these components, movement control and postural correction, share a common output system, changes in one component should be reflected in changes in the other component. Of interest in this paper is the dynamic interaction of movement and postural and the changes in this interaction that are seen in the elderly.

From the theoretical point of view (Lapunov stability theorem) stability is a feature of any system for which sufficiently small changes in the input parameters produce limited changes in the output. In the postural control system, changes in the input are produced by summation of intent (voluntary) and random (postural sway) movements. The random components have been shown to change with age (Sheldon 1963, Welford 1981).

Elderly subjects often experience a well-documented decline in the integrity of many physiological systems that participate in the control of postural stability (Mulch and Peterman 1979, Overstall 1980, Woollacott et al. 1982, 1986, 1988, Cohen and Lessel 1984, Horak et al. 1984, Stelmach and Worringham 1985, Manchester et al. 1989). Age-related neurodegenerative changes in neuromuscular control and a decreased resolution of sensory inputs results in sensory signals that are contaminated with more noise and physiological delays as compared with young healthy subjects (Welford 1981, Blaszczyk et al. 1993, 1994).

Decreased postural stability has been often related to reduced peripheral sensibility in the visual, vestibular, and proprioceptive systems (Teasdale et al. 1993). Additional attentional resources need to be allocated to the postural task when there is a reduction of sensory information available. This increased computational demand on the postural system may increase the time needed to prepare corrective strategies thus decreasing the time for successful completion of a balance recovery program (Overstall et al. 1977, Isaacs 1978, Horak et al. 1984,

Stelmach et al. 1988, Blaszczyk et al. 1992, Teasdale et al. 1993, Inglis et al. 1994).

As the quality of sensory information decreases, postural stability control is increasingly difficult for the elderly and requires a wider margin of safety (Blaszczyk et al. 1994). This in addition to an increased postural sway has a profound effect on the postural stability in the aged and results in their intolerance to changes in the postural system's input parameters (Welford 1984, Blaszczyk et al. 1993).

The motor system, as the output system of the body, is in a prime position to disrupt postural stability and also to compensate for changes in postural input parameters. Because of effects due to motor disruption, in the aging process, movements with greater demands on postural stabilization are gradually excluded (Welford 1984, Blaszczyk et al. 1994). We posit that the execution of a motor program reflects not only external constraints on movement but also the quality of the motor and postural systems. Any impairment or pathology that alters postural stability control must be observed in changes of the voluntary movement strategy. The complex age-related differences in postural stability and in motor control should be seen in measurable biomechanical characteristics that are generated during a repetitive task. The intent of this research is to establish changes in movement strategies related to postural instability in the elderly. Such changes would allow us to evaluate postural stability based upon the movement characteristics.

METHODS

Fifteen elderly (8 males, 7 females; mean age, 72.0 ± 8.1 years) and fifteen young adults (8 males, 7 females; mean age, 22.7 ± 1.6 years) volunteered and signed a University of Wisconsin - Madison approved informed consent form and agreed to participate in this experiment. Elderly subjects were non-institutionalized members of the Madison community; young subjects were students at the University of Wisconsin - Madison. A questionnaire was used to screen subjects with deficits or disorders that might affect postural balance, in particular: history of dizziness or balance problems; history of neurological or movement disorders which might impair performance of the task; recent illnesses or injuries or use of drugs and medications. All elderly subjects maintained an active lifestyle through hiking or jogging (at least 10 miles per week) and regular physical exercises.

A force plate (AMTI OR65-1) was used to record the normal position of the center of foot pressure (COFP) and its displacement during arm movement. PC/AT computer collected data from the force plate and variable resistance apparatus (VRA) *via* a Labmaster analog-to-digital interface and controlled the amount of resistance produced by the VRA. Force plate and VRA data were filtered at 10 Hz and sampled at 25 Hz. Force plate data were used to calculate each subject's COFP path during the task. Based upon measured position data, the root-mean-square velocity (RMS) of manipulandum was calculated.

Subjects performed a cyclic pull-and-push task using a custom built variable resistance apparatus. The VRA consisted of two adjacent hand grips positioned at elbow height and mounted onto a longitudinal rod which allowed horizontal parasagittal movements (Fig. 1). The VRA was constructed in such a way so that it could be used by a subject for postural stabilization during balance loss over a very limited range. A computer controlled electromechanical friction mechanism produced changes in resistance ranging from 0-100 N with a minimum of 100 ms required to implement a change in resistance. Force transducers and position potentiometer were mounted onto the manipulandum; these allowed for resistance and displacement recordings.

Subjects stood barefoot on the force plate in front of the VRA in a comfortable stance. Subject foot placement was then traced to ensure constant foot position during data collection. The experimental task required subjects to perform cyclic push and pull movements of the VRA manipulandum for a period of 20 s per trial. Trials differed by the amount of resistance subjects had to push/pull against and by the speed at which they were instructed to do so. The loads selected were as follows: 2.5, 7.5, 15, 30, 40 and 50 N. Subjects were required to perform three trials of each load. The first trial was performed at a preferred (comfortable) speed; the next trial was performed as fast as possible and the third trial was performed more slowly than the preferred speed. The presentation of loads was randomized and sufficient rest was allowed between trials to minimize fatigue. For more information regarding the above presented method, see reference (Blaszczyk et al. 1994a).

The task was performed under two conditions: while standing upon the flat rigid surface of the force plate, and while standing on a 2.5 cm thick piece of foam placed upon the force plate. There were 54 trials (6 loads, 3 velocities and 3 repetitions) per condition, resulting in a
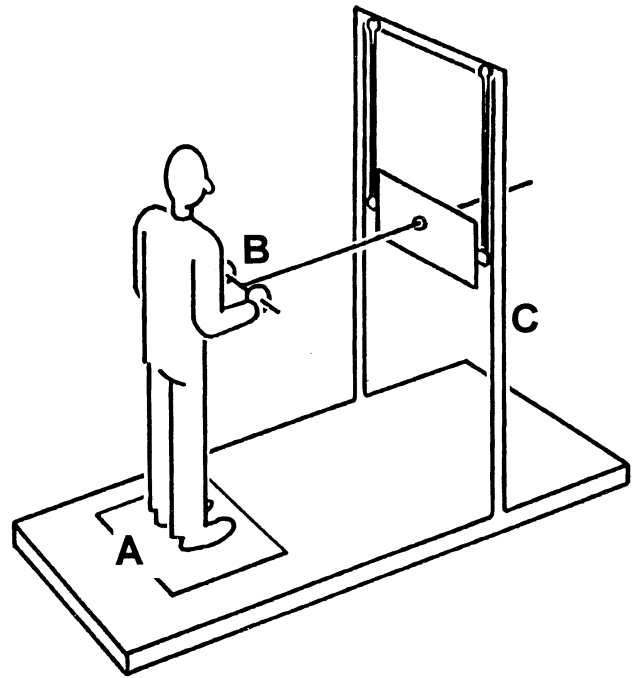

Fig. 1. Schematic of the experimental paradigm. Subject stood barefoot on the force platform (A) and moved the manipulandum (B) attached to the variable resistance apparatus (C).

total of 108, 20 s trials. The amplitude and frequency of COFP displacement in the anterior-posterior direction and the amplitude and frequency of the VRA manipulandum were calculated for each trial. Movement speed and frequency, and amplitude of movement and amplitude of the COFP, were independently analyzed. A three way mixed design ANOVA (type VI - Lindquist 1953) was used, which compared groups (elderly and young), speeds (slow, preferred, fast), and loads. Tukey's test was used for post hoc comparison.

RESULTS

The purpose of this research was to quantify the characteristics of stereotypical arm movements to establish age-related differences in postural stability controls. Statistical analysis revealed some significant intergroup differences in the performance of the experimental task. The manner in which the young and elderly subjects moved the VRA manipulandum depended on the context, which involved external constraints such as the support surface quality and the resistance of the manipulandum.
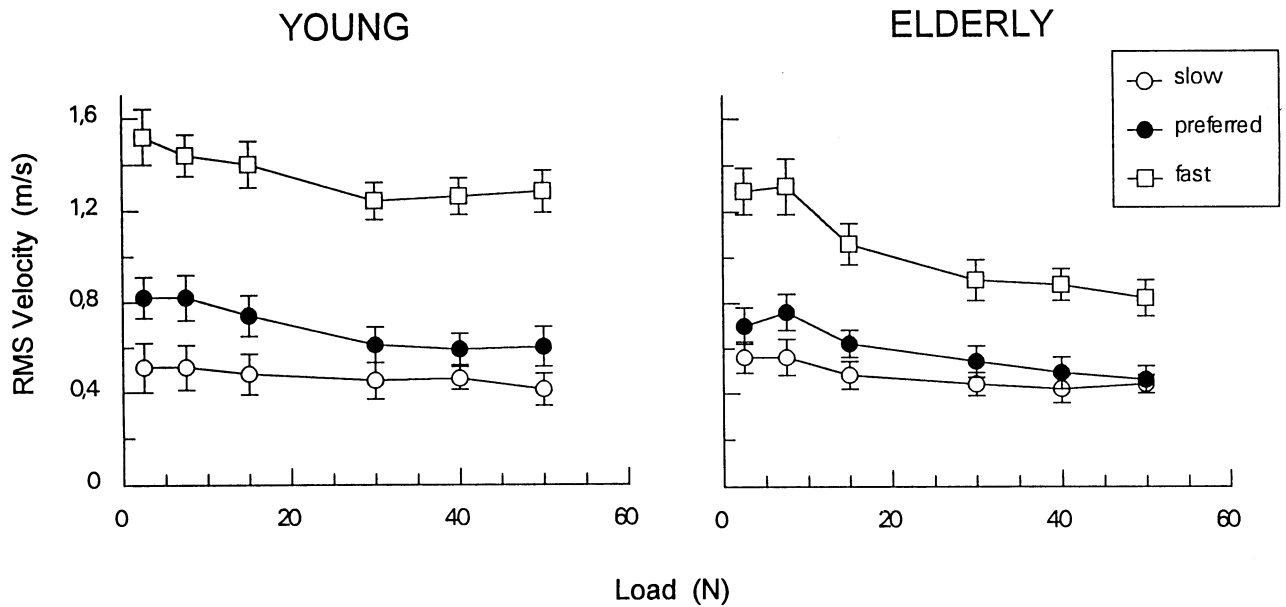
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Fig. 2. Root-mean-square (RMS) manipulandum velocity for young and elderly subjects for each load and speed (slow, preferred and fast) while standing on a rigid surface.

Flat rigid surface

The two age groups studied, differed significantly, in the RMS velocity of the manipulandum during both 'as fast as possible' ($F[1,28] = 153.4$, $P<0.001$) and preferred trials ($F[1,28] = 15.4$, $P<0.001$). Whereas the maximum RMS velocity was 1.04 ± 0.14 m/s in the elderly group, young subjects moved the manipulandum faster with a mean RMS velocity of 1.36 ± 0.09 m/s. There was a significant age x load x movement speed interaction ($F[10,280] = 2.47$, $P<0.001$). Elderly subjects moved the manipulandum more slowly than younger subjects for loads between 30 and 50 N and during the fast movement speed condition ($P<0.01$). There was not a significant difference with the lighter loads up to 15 N (Fig. 2).
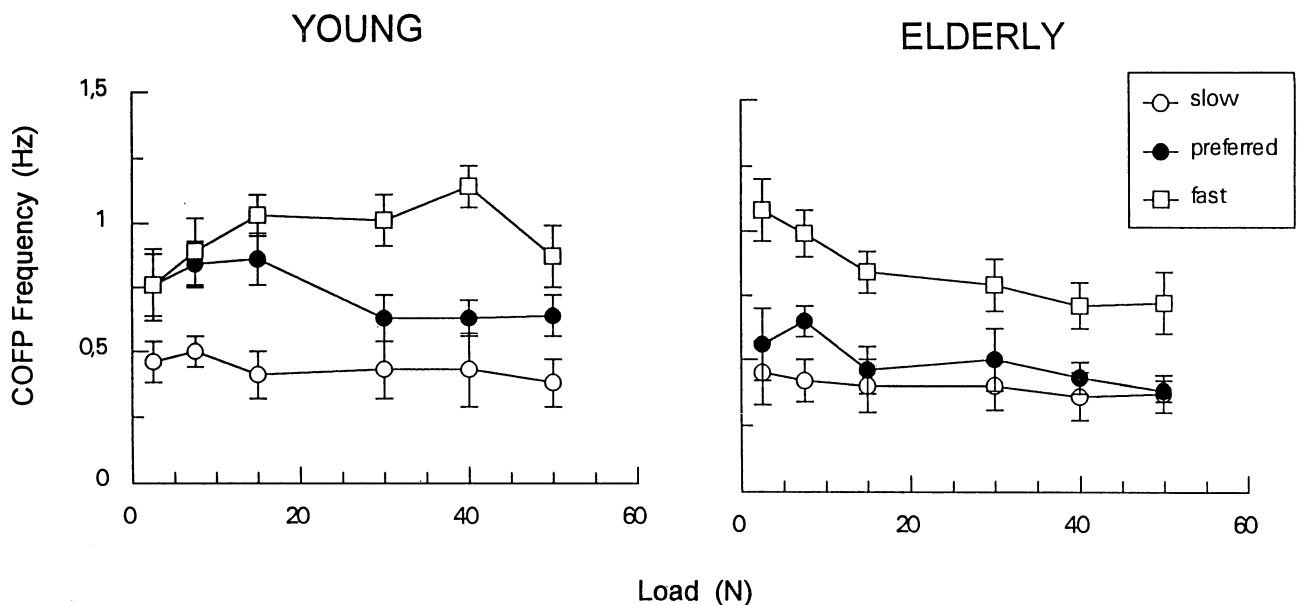
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Fig. 3. Mean center of foot pressure (COFP) movement frequency for young and elderly subjects for each load and speed.

Velocity characteristics include both amplitude and frequency components which can be controlled independently. Analysis of movement frequencies revealed some interesting findings. Cyclic arm movement in the two groups differed significantly in the mean frequency of movement ($F[1,28] = 8.35$, $P<0.01$). The elderly moved the manipulandum at an average frequency of 0.63 ± 0.1 Hz while the young moved the manipulandum at a rate of 0.88 ± 0.13 Hz. Subsequent ANOVAs performed for the particular speeds (i.e. slow, preferred and high) showed that the mean movement frequencies in both groups for "slow condition" were not statistically different. The mean frequency of "as fast as possible" trials in young subjects significantly exceeded that parameter in the elderly subjects (1.07 ± 0.14 Hz in young and 0.87 ± 0.16 Hz in the elderly, $F[1,28] = 11.2$, $P<0.02$). The preferred frequency was also significantly lower in the elderly group than in young subjects (0.48 ± 0.13 Hz and 0.73 ± 0.15 Hz respectively, $F[1,28] = 22.6$, $P<0.001$). Frequency characteristics in both groups are shown in Fig. 3. Statistical analysis revealed also significant age x load x movement speed interaction ($F[10,280] = 6.3$, $P<0.001$). For low resistance we observed an increase of the movement frequencies in young subjects whereas there was an opposite effect in the elderly group.

There was also a significant group difference between mean amplitude of the manipulandum movement, ($F[1,28] = 9.56$, $P<0.005$). While the elderly subjects moved the manipulandum for an average distance of 0.61 ± 0.04 m for each push/pull cycle, the same parameter calculated for the young subjects was 0.67 ± 0.05 m. The cyclic arm movement differentially affected posture in both age groups, and the resultant COFP excursions depended on both the resistance of the manipulandum and the movement rate. Age x load x movement speed interaction was highly significant; $F[10, 280] = 3.37$, $P<0.001$). As shown in Fig. 4 the increase of the COFP range was for the lighter loads (up to 15 N in the elderly and up to 30 N in young subjects) steeper than for the greater loads. What is more interesting, the COFP amplitude was smaller in the young for low resistance (loads of up to 15 N) and then exceeded the elderly's COFP amplitude for loads of 30-50 N.

Foam surface

Destabilization of posture by foam had no effect on the elderly's maximum movement speed whereas in the young subject group the maximum movement velocity decreased to the value observed in the elderly group (compare Figs. 2 and 5). The difference in both groups remained for greater loads ($F[1,28] = 25.7$, $P<0.001$). Similarly as in the rigid surface condition a significant age x load x movement speed interaction ($F[10, 280] = 4.42$, $P<0.01$) for manipulandum RMS velocity was found. Young subjects moved the manipulandum at
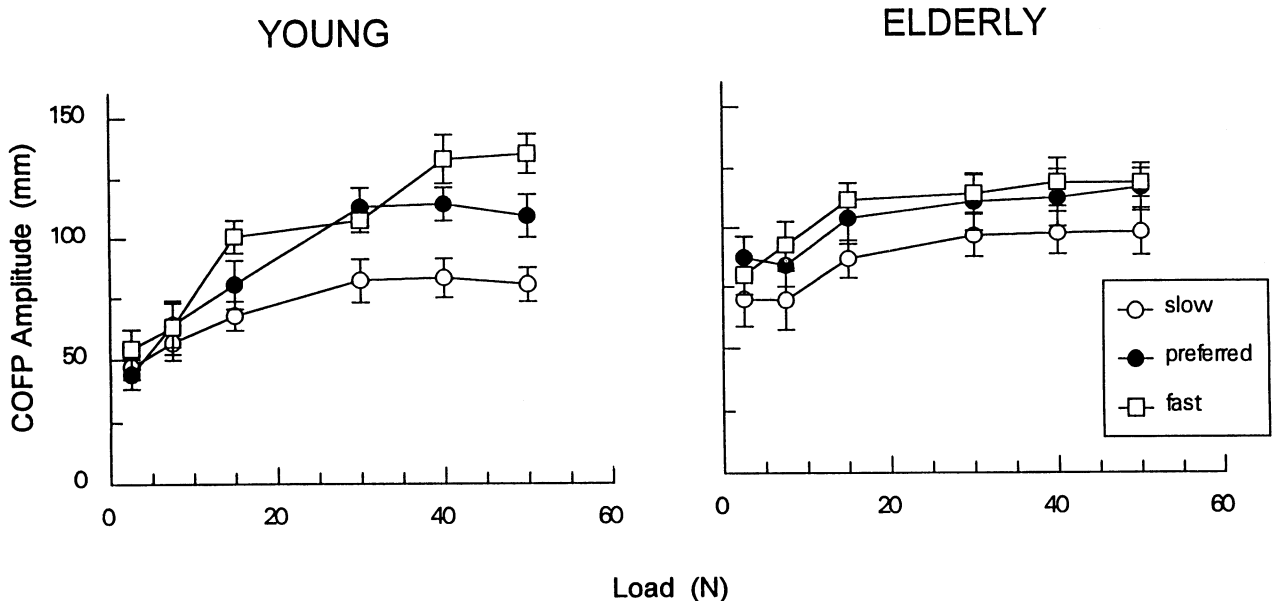

Fig. 4. Mean center of foot pressure movement amplitude for young and elderly subjects for each load and speed while standing on a foam surface.
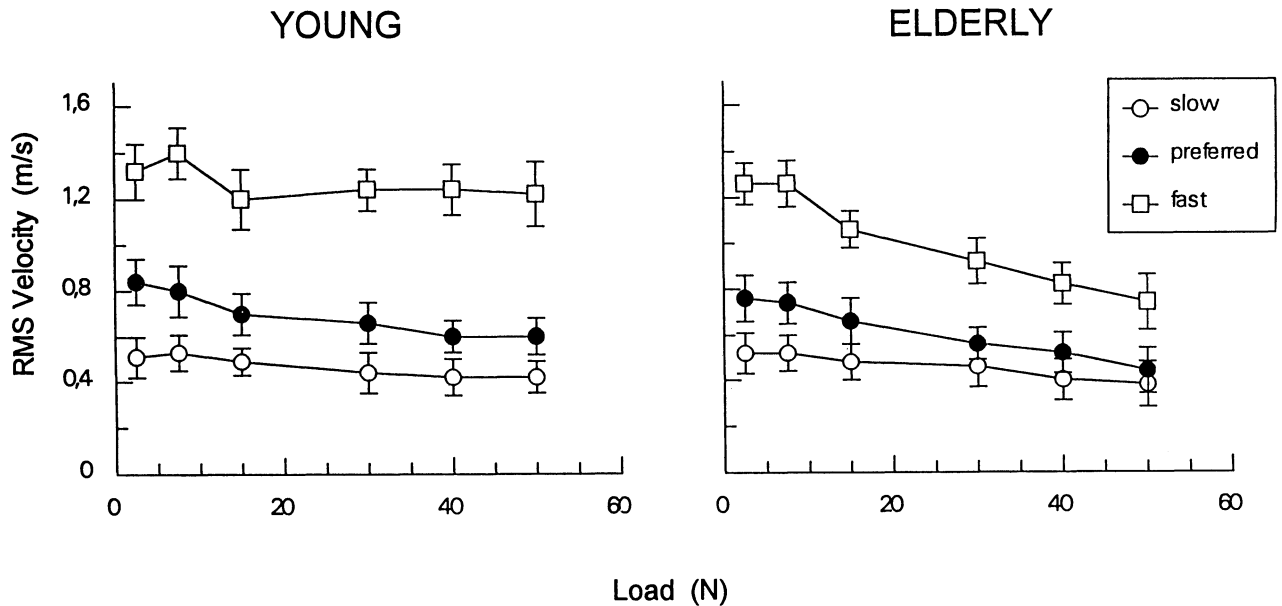
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Fig. 5. Root-mean-square manipulandum velocity for young and elderly subjects for each load and speed while standing on a foam surface.

greater velocities than did the elderly during the fast movement condition for a wider range of loads, i.e., between 15 and 50 N (Fig. 5).

The measured movement frequency was significantly different in young and elderly subjects ($F[1,28] = 6.41$, $P<0.02$). Mean movement frequency was 0.66 ± 0.08 Hz for the elderly and 0.88 ± 0.06 Hz for the young ($P<0.01$). There were no significant age effects or age interactions for RMS velocity and movement frequency. All the values for these variables decreased with increasing load ($P<0.01$). The measured movement ranges in both age groups while standing on the foam were not statistically different.

Within the young group, however, there was a significant surface effect ($F[1,14] = 7.44$, $P<0.01$) for mean amplitude of COFP excursion (109 ± 12 mm on the flat surface vs. 85 ± 7 mm for the foam).

DISCUSSION

In the performance of arm movements against a load almost the entire musculature of the body is engaged. Some of these muscles are also involved in postural stabilization. Thus the changes in movement characteristics as observed in our study can be explained in terms of muscle strengths, acuity of the sensory inputs, and speed of signal processing in the nervous system etc. However, the same factors determine postural stability (Blaszczyk

et al. 1994) and therefore in our discussion we shall relate our findings to postural stability, which is a global measure, rather than to a single factor such as muscle strength.

The implementation of a motor program allows for the indirect evaluation of postural stability. Some details concerning upright postural stability while performing controlled motor tasks can be achieved by means of a dynamic stabilogram - a plot of time-varying, movement induced, displacements in coordinates of the COFP (Lee et al. 1990). Typical experimental protocols associated with dynamic posturography and involving displacement of a support surface are considerably hazardous and physically taxing, thus application of such studies in the elderly population is rather limited. Transient tests may also elicit anxiety that could affect performance (Maki and Ostrovski 1993). From this perspective we decided to use a continuous perturbation induced by the subjects themselves.

The dynamic stabilogram is a measure of whole-body dynamics thus its applicability to postural stability evaluation might be questioned. In the present research, the problem of characterizing dynamic stabilograms is approached from the perspective of control theory. In particular, it is postulated that the comparison of COFP displacements evoked by controlled cyclic arm movements in young and elderly subjects can be used to evaluate any age-related differences in postural stability.

Since COFP is a measure of whole body dynamics, it represents the summed effect of a number of different neuromuscular components acting at a number of different joints (Lee et al. 1990, Collins and De Luca 1993). It has been explicitly noted in the discrete pulling studies of Lee et al. (1990) that the body and COFP motions that accompany pulling are causally related to force production at the handle, not just to the maintenance of balance. It should be remembered, however, that the human body creates an active kinematic chain that transmits most of the torques produced during a motor activity to the base of support (Cordo and Nashner 1982). Transmission of the mechanical signals through the dynamical multi-linked system of the body is modified by compensatory effects due to delays in the muscular system, intersegmental inertial torques, coriolis effects and centripetal forces etc. The final effect of this transmission is observed at the base of support as a compound COFP signal.

The execution of the controlled voluntary arm movements and resulting COFP excursions from its normal position may have some inferences for the control of postural stability (Maki and Ostrovski 1993). ,Equilibrium control consists of keeping the body's center of gravity (COG) within the limited area of the base of support (Massion 1992). It has been suggested that the postural control system acts to maximize the stability margins, i.e. the distance between normal COG position and the borders of the base-of-support (Koozenkanani et al. 1980, Blaszczyk et al. 1992, 1994). The range of the COG excursion as exhibited by COFP displacements depends upon voluntary movement parameters such as amplitude and speed. Thus, when performing pull-and-push movements against a controlled load, subjects challenge their equilibrium within a range that is limited by individual neuromuscular, biomechanical and cognitive factors.

A well documented decline of postural stability in the elderly has a profound effect on the characteristics of motor activity. This was seen in our data, in the differential performance of the cyclic arm movement for different loads. The increase of VRA resistance has two main effects. First, a freely standing subject's equilibrium is upset whenever he grasps and then exerts force on an external object. Destabilization increases with increased resistance of the manipulandum. On the other hand, we may think of each point of physical contact between the subject and support as a potential point of application of a stabilization force (Jeka and Lackner 1994). For in-

stance, in some patients stability can be improved by allowing them to touch a fixed surface lightly with a single finger (Nashner 1983).

The movement speed characteristics investigated in our experiment, can be divided into two domains which differ significantly in their requirements for postural stabilization. In the domain of low movement resistance (up to 15 N), the main requirement was mostly placed on postural stability and for the higher loads the performance depended mainly upon the force output produced by the subject. In the first domain the elderly clearly exhibited decreased COFP position control. In this group, despite a reduced arm movement range, a higher amplitude of COFP excursions were observed. This means that an upright posture in the elderly was destabilized more than in young subjects by the same or a weaker perturbation.

The resultant COFP movement depends on both the resistance of the manipulandum and the movement rate. The COFP range typicaily increases in response to an increase in VRA resistance. The slope of the COFP amplitude increase with load was different for young and the elderly. This was true in both age groups for slow and preferred velocities.

Another characteristic feature of motor activity in the elderly is the slowness of movement. We claim that the preferred speed is a sensitive measure of the state of both motor and postural systems. The decrease in the preferred frequency in the elderly was greater than could be expected from maximum frequency changes. Such alterations of the frequency characteristics suggests that the elderly may have adopted a "slowness strategy". This strategy shift hypothesis is in contrast to the hypothesis that the elderly's balance was altered by pure physiological constrains (Mankovski et al. 1980, Inglin and Woollacott 1988, Massion and Dufosse 1988, Stelmach et al. 1988, 1990). Further research is needed to evaluate the role that each of these hypotheses play in the changes that are seen in the performance of motor tasks in the aged.

Ground reaction forces are, no doubt, dependent on the quality of the support surface. A rigid surface allows for a better stabilization of the upright posture. A foam surface may introduce marked delay in compensation for destabilizing torques since support reaction force is modified by the viscoelastic properties of foam. Also changes in proprioceptive patterns while a subject is standing on a foam surface may additionally impair postural stability. It is probably for these reasons that we ob-

served a slowing down of the arm movement velocity in young subjects during the fast movement condition performed on a foam surface. This effect was not observed in the elderly group since the elderly performed the experimental task on both rigid and foam surfaces more cautiously (with a wider margin of safety).

In conclusion the data presented here show that the movement characteristics and movement-related COFP excursions may be considered a veridical measure of postural stability. The efficiency of this method has been verified by comparing the results of the pull-push arm movement task in the two age groups that differ significantly in their postural stability. The reduction of movement range and speed, with a concomitant increase of the COFP amplitude, illustrate the functional manifestation of postural stability decline in the elderly.

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