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ACADEMIC LITERATURE REVIEW

Aging-related temporal constraints to stability and instability in postural control

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Abstract In this study, we review the evidence that older adults tend to have both a shorter time to lose stability in the maintenance of standing posture and the functionally related but inverse problem of needing more time to reacquire stability in transitioning to a postural state. These age-related time limitations to processes of stability are hypothesized to enhance the probability of falling with aging and the problems that can occur in the transition between activities, such as sitting to standing and standing to walking. The potential role of fitness and health variables in mediating the temporal constraints on the acquisition and loss of postural stability in aging is discussed.

Keywords Aging · Posture · Stability

The conduct of daily life involves the engagement in a variety of physical activities that have been historically categorized into subgroups, such as activities of daily living, work, sport, music, and play. These activities in all contexts are manifestations of the fundamental physical activities of posture, locomotion, and manipulation. Thus, even in a single day in the lifetime of an individual, that person switches from the execution of one action to another in a sequence and time course that is determined by many environmental and individual factors. This time course of the change in behavior over time implies that an individual in switching activities is also caught in the continually evolving dynamical spiral of moving from stability to instability to stability and so on. The temporal limitations in acquiring or moving away from stability in standing posture as a function of aging is the focus of this review.

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It is well established that aging tends to lead in most individuals to a number of limitations and problems in the conduct of perceptual motor skills. The information processing [1–4], neurophysiological [5, 6] and fitness [7–9] perspectives to aging and physical activity have all revealed age-related trends including: poorer performance (no matter how it is measured), slowness of thought and action, and loss of fitness properties such as strength, flexibility, and endurance. The more recent emphasis on dynamical processes of aging through the metaphor of self-organization has opened up new approaches and findings to aging-related limitations in physical activity [10–15]. A particular thrust has been the investigation of age-related changes in the complexity of behavior through a consideration of the evolving dynamics of movement in action [12, 16], with emphasis on the health outcomes of dynamical stability and instability. Glass and Mackey [10] have viewed some processes of aging and movement disorders as an example of a dynamical disease in which behavioral and physiological systems change as a consequence of aberrations in the temporal organization of the evolving dynamics.

The role and consequences of dynamical stability and instability are magnified in whole body physical activities such as standing posture and locomotion because of the potential severe negative consequences of injury that can arise from falling [17]. Falls are an extreme example of the loss of stability in physical activity and provide the health-related background to this review of the effect of aging on both the time to stability and the time to instability in standing posture. As one might anticipate in elaborating from the traditional age-related deficits in performance, the evidence reveals that older adults tend to have both a shorter time to losing stability in the maintenance of a postural state and the functionally related problem of taking more time to reacquire stability in assuming a postural state.

Aging and the time to instability in postural control

To sustain standing posture, the muscles of the postural control system must support the body against gravity, stabilize the supporting elements of the body when other elements are moved, and ensure that the body is balanced through the vertical projection of the center of gravity lying within the base of support [18]. Instability is realized qualitatively when the projection of the center of gravity moves outside of the boundary that defines the stable base of support. However, instability can also be defined quantitatively in a dynamical framework with various measures (such as Lyapounov exponent) that capture the degree of departure of the trajectory dynamics from the attractor and hence the relative stability and instability [19].

The determination of the stability of standing posture is most usually calculated from force platform data in the form of the dynamics of the center of pressure and the evolving location of the vertical ground reaction force at the surface of support in standing. In laboratory standing-still tasks, the motion of the center of pressure provides an index of the motion of the center of gravity of the body but it is not itself a measure of the center of gravity. The stability of standing in this framework is typically determined by measures of the amount of variability of the center of pressure or more particularly the position of the center of pressure relative to the stability boundary of standing.

There have been several ways proposed to determine the stability boundary for the motion of the center of pressure. The most common approach is geometric in that it is determined relative to the spatial area that is formed from the position of the feet on the surface of support. Barin [20], for example, used this geometric approach as shown in Fig. 1. Thus, instability is realized when the location of the ground reaction force on the horizontal surface of support moves outside the geometric boundary as formed by the area of the position of the feet.

This traditional approach to determining the instability of standing posture holds several limitations. First, the geometric boundary as defined by the feet is only an approximation of the functional stability boundary for an individual, which is more appropriately determined by the functional capacities of the individual. The geometric boundary is not the same as the limits of the functional boundary so that individuals with the same foot boundary (and hence stability area) would likely have *different* functional boundaries due to individual differences, such as height, strength, and so on. Second, this method in using the location of the center of pressure relative to the boundary does not consider the temporal constraints of the motion of the center of pressure in the determination of stability. The center of pressure could be close in a position frame of reference to the boundary but not actually be moving toward the boundary, leaving it a poor estimate of the instantaneous functional stability of the standing posture.

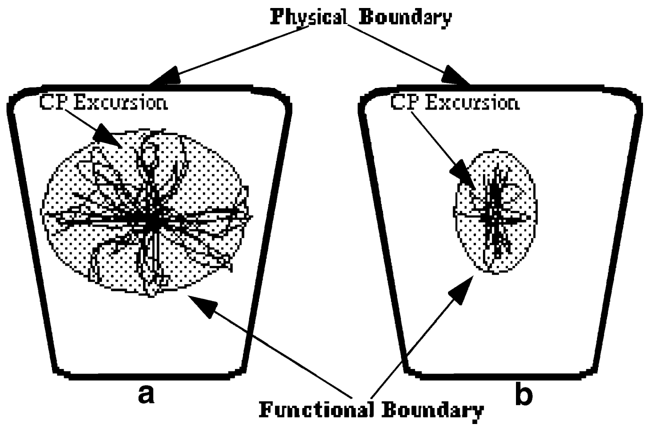

Fig. 1 A schematic showing the geometric base of support formed from the position of the feet and the functional base of support formed from extreme postural sway trials

Slobounov et al. [21] developed a method to determine the *virtual time-to-contact* (VTC) to the stability boundary in a three or even *n* dimensional space and applied this method to the estimate of postural stability in human standing posture. This method was applied to the motion of the center of pressure but it can also be used to assess the motion and stability of the center of gravity or other human movement properties. The motivation for such a method came from the theoretical principles of the ecological approach to perception and action [22].

The ecological approach to action places the emphasis on information for control not on departures from a stability point within the equilibrium region of the potential base of support, as in inverted pendulum models of posture, but rather on the temporal safety margin, as specified by the virtual time to collision with the stability boundary [22, 23]. A significant consequence of this approach is that the control variable for posture is defined over the organism–environment task interaction rather than simply a product of the organism [24, 25]. Initially, Carello et al. [26] postulated that the time to contact with the stability boundary may be the low-dimensional information control variable in postural regulation, and this hypothesis was initially taken up experimentally by Martin [27] and Riccio [25].

Slobounov et al. [21] calculated VTC as the instantaneous time to the functional stability boundary defined on the dynamics of each point in the time series (see the appendix in [21] for full details on the calculation of VTC). The word virtual was used because the individual does not want to actually make contact with the stability boundary, and so VTC is an estimate of the time to the boundary *should* it occur. This contact with the boundary would only happen in the case of a loss of stability as in a fall or change of postural mode. In this approach, a time series of the VTC can be determined that is based on the dynamics of the time to contact relative to the boundary rather the relative position of the center of pressure to the stability boundary. Figure 2 provides a schematic of the calculation of the VTC measure against the geometric boundary. The same strategy to calculate VTC can also be used against the functional boundary. In the initial Slobounov et al. study [21] with students, it was shown that the coefficients of variation of the VTC were lower than those of the velocity and acceleration of the center of pressure. The robustness of the VTC in human single-leg quiet standing has been demonstrated [28].

Slobounov et al. [29] subsequently built on this theoretical and empirical background and investigated the VTC in standing-still posture as a function of cohort group (60–69, 70–79, 80–89, and 90–96 years of age). The functional stability boundary for each participant was initially determined through having the individuals lean as far outward as they could in all directions without falling. Then the VTC from the center of pressure was calculated in standing-still trials against this individually specified functional stability boundary under different conditions.

One indication of the more highly constrained stability boundary conditions as a function of aging can be found in Fig. 3 which shows the ratio of the area of the center of pressure from standing still/area of the stability region (with between-subject standard deviations) as a function of age group and vision condition. The findings show that with increasing age, the motion of the center of pressure fills a higher proportion of the potential stability region. In other words, the spatial margin of the available center-of-pressure motion is reduced with advancing age. This aging effect

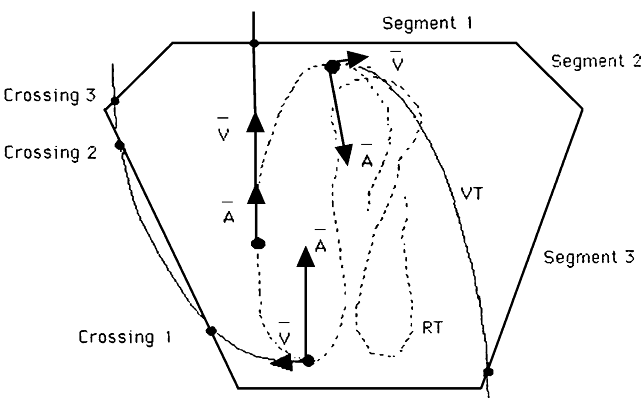

Fig. 2 A schematic of the VTC calculation to the geometric boundary (adapted with permission from Slobounov et al. 1997 [21])

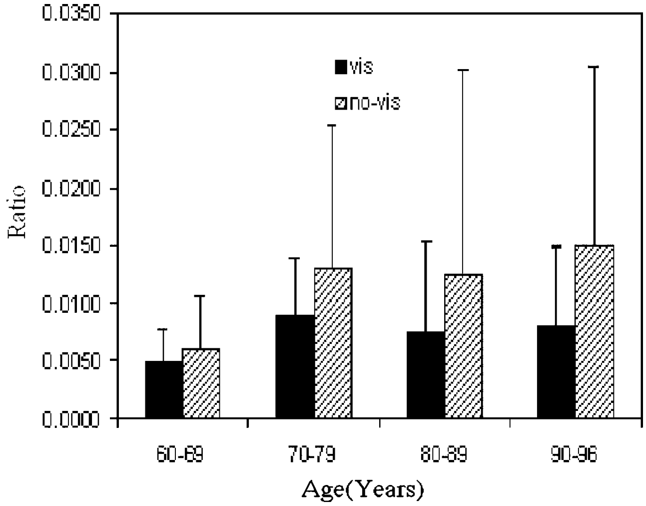

Fig. 3 The ratio of the area of the center of pressure/area of the stability region (with between-subject standard deviation) as a function of age group and vision condition (adapted with permission from Slobounov et al. 1998 [29])

occurs because of the combined effects of a great variability of motion of the center of pressure with age (e.g., [30]) and the declining area of the stability region (see also [31]). These effects are magnified in the eyes closed as opposed to the eyes open condition.

Figure 4 shows the VTC as a function of age group and vision condition. The data clearly support the conclusion that VTC declines with advancing age. This means that the older adult has less of a temporal safety margin with respect to crossing the stability boundary, a factor that could lead to a step to try to recover stability or in the worst case scenario a fall. This effect of reduced VTC should also be considered against the well-established finding of a longer reaction time in advanced age [1, 3].

It is instructive to note that while withdrawing vision reduced the functional area within the stability boundary across the age groups, there was no vision effect on the VTC within an age group. The contrast of the age effects for the spatial area and time measures provides another indication that the VTC may be the more fundamental measure in the control of postural stability. Van Wegen et al. [32, 33] using a variation of this VTC measure have shown similar age-related properties of time to contact in the control of postural stability.

Newell et al. [34] modeled the stability of standing posture as a function of age, including older adults (60–80 years of age). The stochastic processes of postural center-of-pressure profiles were examined in 3- and 5-year-old children, young adult students (mean 20 years), and an elderly age group (mean 67 years). Subjects stood still in an upright bipedal stance on a force platform under vision and nonvision conditions. The amount of motion of the center of pressure decreased with increments of age from 3 to 5 years to young adult but increased again in the elderly age

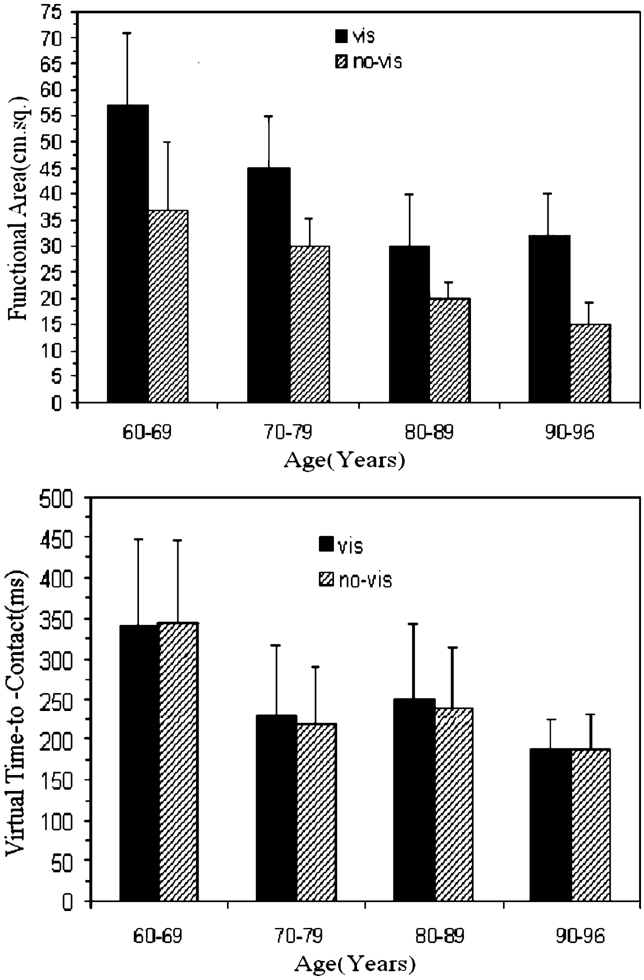

Fig. 4 *Top* The area (square centimeters) of the functional stability region (with between-subject standard deviations) as a function of age group and vision condition: *Bottom* Mean VTC (milliseconds) calculated against the functional stability region as a function of age group and vision condition (adapted with permission from Slobounov et al. 1998 [29])

group. The availability of vision decreased the amount of motion of the center of pressure in all groups except the 3-year-old group, where there was less motion of the center of pressure with no vision.

The stochastic properties of the center-of-pressure dynamics were assessed using both a two-process, random-walk model of Collins and De Luca [35, 36] and an Ornstein–Uhlenbeck model that is linear and has displacement governed only by a single stiffness term in the random walk. The two-process, open- and closed-loop model accounted for about 96% and the Ornstein–Uhlenbeck model 92% of the variance of the diffusion term. Diffusion parameters in both models showed that the data were correlated and that they varied with age in a fashion consistent with developmental accounts of the changing regulation of the degrees of freedom in action [30]. The findings suggest that it is premature to consider the trajectory of the center of pressure as a two-process, open- and closed-loop random-walk model given that: (a) the linear Ornstein–Uhlenbeck dynamic equation with only two parameters accommodates almost as much of the variance of the random walk, and (b) the linkage of a discontinuity in the diffusion process with the transition of open- to closed-loop processes is poorly founded.

These studies provide an indication of not only the temporal constraints on the stability of standing posture but also that advancing age in adulthood provides narrower temporal safety margins in the regulation of standing. These effects have been demonstrated in what is typically considered the most stable standing mode, namely, standing still with the feet side by side at a width of self-choice in a predictable environment. It seems reasonable to postulate that these age effects on the temporal margins of postural control will be magnified further in the regulation of less stable postures, such as the Rhomberg or one leg stance. Similarly, a changing and less predictable environment would also probably magnify the age-related effects of VTC. These effects, if realized, would support the general idea of the confluence of constraints interacting to determine the boundary conditions of physical activity [24], as expressed here in upright standing.

In closing this section, it should be recognized that the VTC measure seems to be a good candidate for a low-dimensional variable that is used to regulate standing posture [26]. A standard criticism of this hypothesis, however, is that the results to date, such as those reported above for VTC, are correlational and not causal about the dynamics of postural control. This criticism, although equally applicable, is rarely applied to pendulum models of posture, which dominate the literature [e.g., 37]. In this regard, it is noteworthy that Patton et al. [38] have outlined a model for human postural control that is driven by the use of safety margin information to the stability boundary in the regulation of standing posture.

Furthermore, postural stability has also been investigated in the limb postures such as the clinical protocol of finger, hand, or arm tremor [5, 39]. The VTC and the time to reacquire stability measures have not been measured in these clinical postural tasks as a function of age but the changes in postural dynamics with aging appear similar across tasks [13]. This may be because there is clearly a different clinical and personal consequence to losing the postural stability of finger control in a clinical test in contrast to the consequences of a fall in standing posture.

Aging and the time to stability in postural control

The engagement in and the task requirements of performing activities of daily living require the continual change over time in an individual's movement patterns. This is no more apparent than in the kitchen of a home where an individual may be switching between standing, walking, turning, lifting, and so on in a relatively short period of time in the support of, for example, just cooking a dinner. It is probably not a coincidence that the home, particularly the kitchen, is a high probability environment for falls [40], which, as we have said, is the extreme illustration of the loss of stability.

The task goal of reacquiring stability is emphasized in the transition of activities such as the change from walking to standing. Historically, the human movement domain has been studied in both young and old adult locomotion [41–43] and standing posture [e.g., 44–47] separately with little emphasis on the reacquisition of postural stability following a step or sequence of steps. Nevertheless, it is well known that older adults experience more problems with postural control when they are required to move through or change their position with respect to the environment [40, 48].

One background clue to the notion of age-related problems in the time to reacquire stability comes from the observations that several features of the gait pattern change with increasing age. It is well established that older adults tend to adopt a more conservative gait pattern as reflected in a decreased step or stride length, increased stride width, and slowed gait speed [49–51]. Indeed, there is a reduction of about 4% in step length between the ages of 20 and 60 years and a reduction of 6% between the ages of 60 and 70 years [52]. These changes in the gait pattern are consistent with, but not direct evidence for, the hypothesis that the stability of the typical healthy young adult pattern cannot be maintained with the constraints of aging, and so to preserve stability in the execution of the activity, there is a change to a more conservative gait pattern.

Johnson et al. [53] conducted an experiment to investigate the influence of aging (cohort groups 20–29, 60–69, 70–79, and 80–89 years of age) on the time needed to reacquire postural stability. The experiment examined the regaining of postural stability after a single step had been performed. The act of taking even a single step from a stationary and stable postural state required the individual to in effect lose balance or stability and regain a stable state once the step had been completed. This transition of losing and regaining stability occurs whenever an individual makes postural changes and takes single steps before assuming a new postural state in a variety of contexts.

The participants were asked to take a single step of varying lengths from a stationary standing posture from a surface that was horizontal with and adjacent to a force platform. The preferred step length was determined, and two levels above (preferred step length plus 5 and 10%) and two levels below (preferred step length minus 5 and 10%) were observed. A block of three trials was performed for each of the five step-length conditions. The trial lasted for 45 s in duration, and the force platform data were collected from the initiation of the step. The key variable analyzed with respect to the evaluation of the reacquiring of stability on the taking of the step was the time it took to bring the velocity of the center-of-pressure motion to 6 cm/s for a duration of 4 consecutive seconds.

Figure 5 shows the mean time (with standard deviation) of instability as a function of age group and step length. The findings clearly reveal that the mean time and the between-participant variability in the time to reacquire stability increased as a function of cohort age group. There was no significant effect of step length on the duration of time to reacquire stability. These results provide strong evidence that the time to reacquire postural stability from the taking of a single step under very typical, undemanding flat-surface conditions increases with age.

The Johnson et al. [53] study also recorded measures of self-efficacy (Falls Efficacy Scale) and general confidence (Activity-Specific Balance Confidence Scale) in balance activities. Correlation analysis showed that older adults were less confident in their ability to complete daily activities without falling or losing balance and that participants with lower levels of balance-related efficacy required a longer time to reacquire stability. These findings provide evidence that individual's perceptions of balance and falls efficacy are related to the temporal limitations in the regaining of postural stability.

A parallel set of age-related (cohort groups 20–29, 60–69, and 70–79 years of age) findings with regard to the time to reacquire stability has been found by Haibach et al. (manuscript under review) who investigated the effect of a visual perturbation in a virtual reality environment on the stability of standing posture using essentially the same

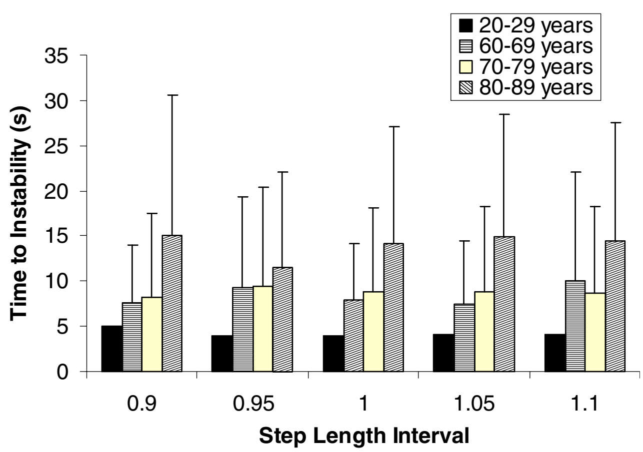

Fig. 5 Mean time to stability (with standard deviation) as a function of age group and step length (expressed as a ratio of preferred step length) (adapted with permission from Johnson et al. 2003 [53])

force platform protocol. The virtual room moved discretely in the anteroposterior plane from the participant and oscillated sinusoidally for 12 cycle moving toward and away from the participant. The frequencies and amplitudes were crossed over the combinations of 0.3 and 0.6 Hz and 9 and 18 cm, respectively. The trial duration was 25 s after the perturbation, and the force platform recordings were initiated 5 s before the visual room perturbation. The time to stability was determined as in Johnson et al. study [53] except that the criterion used to index the acquisition of stability was on a subject relative as opposed to an absolute basis. Stability was taken to be realized when the center-of-pressure velocity remained below three SDs of the velocity present in standing still without the visual perturbation.

The results clearly showed that young adults exhibited significantly less postural motion than both of the older age groups and required the least amount of time to return to stability after the discrete visual perturbation. In contrast, the older adults took the longest amount of time to return to the stability criterion. Overall, the mean time to stability was on the order of about 10–15 s as it was with the physical perturbation of taking a step (Johnson et al. [53]). In addition, both older age groups were less able to compensate from visual perturbations, leading to increased time in an unstable position. It was also shown that the older adults were less able to anticipate the need for postural adjustments than the young adults, placing them at an increased risk for the loss of stability after a visual perturbation.

The findings from the step perturbation of Johnson et al. [53] and the visual perturbation of Haibach et al. (manuscript under review) show consistently that the time to reacquire stability increases with the increments of age in older adults. This systematic age-related effect was realized in the relatively constrained environment of a discrete step and visual perturbation. The perturbations of these studies are relatively simple when contrasted with situations in the contexts of the lifestyle of most individuals and yet by the criteria used to determine the reacquisition of stability it still took about 10–15 s to realize this state. Clearly, there are different strategies that could be invoked to determine the return to stability but the techniques employed in this study suggest a relatively longer time duration to return to stability in the elderly subjects. Indeed, 10–15 s is probably beyond the duration that most individuals stay in a given postural state in the time course of daily events. If this latter projection is the case, then it means that the time constraints of the switch between activities lead to individuals rarely being in a stable postural state in a dynamical sense even if the participants have not progressed to the problematic condition of a fall. If this analysis holds any relevance, it places enhanced constraints on the boundary conditions of postural stability in older adults.

Individual difference mediators of stability/instability in posture

The effects of aging on motor performance properties are most usually investigated with what are loosely characterized as healthy aging adults. However, with increasingly rigorous inclusion/exclusion criteria in aging studies, this means that the population make-up of the healthy aging group is becoming more narrowly defined. One consequence is that the population pool is narrowing with the older age groups, and this in and of itself could influence the interpretation of mean cohort age effects on dependent variables. The older age groups, however, even with the healthy aging criteria, still tend to show behavior and performance differences from their younger cohort groups at least when evaluated on a mean basis.

The experimental approach reviewed in this study on the temporal limitations to stability and instability is predicated on the independent variable of chronological age as the only or primary index of aging. Furthermore, most of the studies on aging reviewed and more generally those on other aspects of posture and location are cross-sectional. Thus, the full array of experimental designs has not been implemented to tease out the real age-related effects on most properties of physical activity. The significance of this limitation is compounded by the fact that it is becoming increasingly recognized that chronological age is a poor marker of biological aging [Haibach et al. (manuscript under review); 54–56].

In effect, chronological age effects provide an entry rather than a solution to understanding age-related decrements in physical activity and behavior. Chronological age in and of itself is, therefore, not the primary variable causing changes in the control of movement. Clearly, there are a range of possible candidate variables that on average are correlated with age effects, including the much studied information processing deficits [1] and the physical fitness limitations of declining strength, flexibility, and endurance [9]. Typically, however, these variables are not studied in a standard individual difference approach to the behavior and performance deficits that have been associated with aging.

One exception to this norm is the recent work that has explored the hypothesis that there is a strength and force variability relationship in advanced age. This hypothesis on the mediating role of strength in motor control is based on several empirical findings. First, in reports that find minimal age differences in force control between young and old adults, there also are typically no age differences in strength [e.g., 57]. Second, strength and activity training that led to increases in strength has been found to decrease age differences in force variability [e.g., 58]. Third, the fitness level (a proxy index of strength) of older subjects is often relied upon to explain discrepancies in age effects between studies [6]. These points collectively give support to the hypothesis that strength mediates both organization and output performance in physical activity.

The findings of Sosnoff and Newell [59] showed that the isometric finger force variability of older adults (60–80 years) was greater and showed less time-dependent structure than their younger counterparts. The force output of weaker subjects was also more variable and had a stronger time-dependent sequential structure. However, when maximal voluntary contraction was controlled for statistically, there was no significant age effect on force variability. In contrast, the relationship between strength and variability remained significant when chronological age was statistically controlled. These findings lead to the conclusion that the age-related changes in force variability are more fundamentally a result of the association between strength and force variability rather than chronological age and force variability. Indeed, the findings provide a challenge to the theoretical rationale of using chronological age as a marker of the biological aging process in studies of motor control.

The study of the temporal constraints to aging effects on the loss of stability and the difficulties in reacquiring stability would benefit from an approach that a priori selects participants on key variables that are hypothesized to mediate the behavior. The challenge will be the rationale for the constructs selected for the study but at least with this approach, we will begin to understand the relative contribution of information and physical fitness properties to what are now characterized as age-related effects. This approach may also contribute to understanding the contribution of cohort effects to age-related effects.

Concluding comments

The review reveals that older adults tend to have both a shorter time to losing stability in the maintenance of a postural state and the functionally related problem of taking more time to reacquire stability in assuming a postural state. The time scale of losing stability in standing posture is considerably shorter than that of reacquiring a stable postural state. Currently, there is no evidence for these temporal limitations on a within-participant basis but the postulation is that the changing time constraints on stability as a function of aging is a general limitation or process deficit in motor control. This temporal limitation is coherent with other changes in the complexity of movement dynamics with aging and their associated links to performance decrements and frailty [13].

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