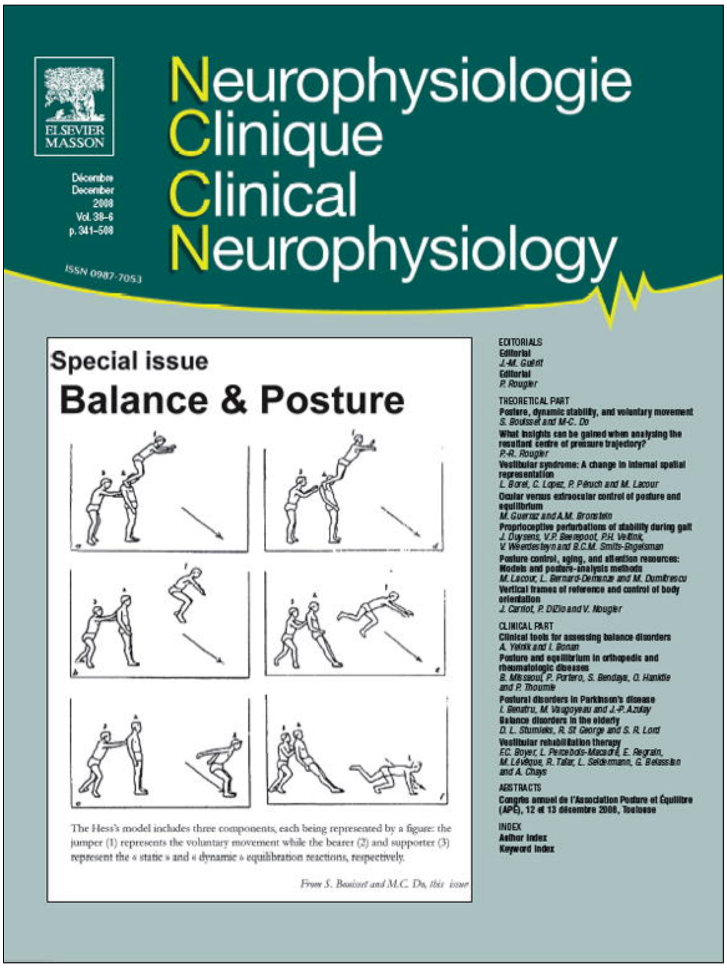
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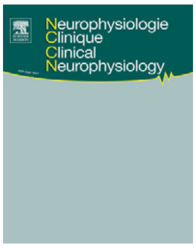

REVIEW/MISE AU POINT

# Posture control, aging, and attention resources: Models and posture-analysis methods

# Contrôle postural, vieillissement et charge attentionnelle : théories et méthodes d'analyse de la posture

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**Summary** This paper reviews the literature on balance and cognitive function in normal aging. The first part provides a general background of dual tasking (postural performance under a concurrent cognitive activity) and summarizes the main relevant models capable of explaining the poorer postural performance of older-healthy adults compared to younger-healthy adults: the cross-domain competition model, the nonlinear interaction model, and the task-prioritization model. In the second part, we discuss the main limitations of the traditional-posturographic analyses used in most of the dual-task investigations and explain how these can account for some discrepancies found in the literature. New methods based on the stabilogram-diffusion analysis and the wavelet transform are proposed as better approaches to understand posture control. The advantages of these new methods are illustrated in young adults and elderly people performing a simple postural task (quiet standing) simultaneously with a mental or a spatial task.

MOTS CLÉS
Vieillissement ;

**Résumé** Cet article de synthèse est centré sur le contrôle postural et les processus attentionnels au cours du vieillissement. La première partie est une revue générale de la littérature portant sur les données recueillies chez des jeunes adultes et des adultes âgés en utilisant le paradigme expérimental de double tâche. Les principaux modèles, expliquant les modifications

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Contrôle postural ;
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du contrôle postural avec l'âge lorsqu'une tâche cognitive doit être réalisée simultanément, sont présentés : le modèle de compétition ou de partage de la charge attentionnelle, celui de processus interactifs non linéaires entre tâches et celui de la priorité donnée à l'une des tâches (le contrôle de la posture avec l'âge). Dans une seconde partie, sont exposées les principales limitations des techniques et outils traditionnels d'analyse du contrôle de la posture utilisés dans les études en double tâche, qui pourraient rendre compte de résultats en apparence contradictoires rencontrés dans la littérature. De nouvelles approches mathématiques d'investigation de la posture sont présentées ; elles sont basées sur l'analyse de diffusion et la méthode des ondelettes appliquées aux signaux stabilométriques. Les avantages de ces nouveaux outils dans des investigations en double tâche sont illustrés chez de jeunes adultes et des personnes âgées, réalisant simultanément une tâche posturale simple (se tenir debout immobile) et une tâche cognitive de calcul mental ou de représentation spatiale.

## Background and models

### Postural control and cognitive demand

The posture-control system regulates the body's position in space for the purpose of orientation and balance. It is based on the central integration of vestibular, visual, proprioceptive, and tactile information and on an internal representation of the body's orientation in space. The internal model of the body's position is continuously updated on the basis of this multisensory feedback and this internal representation is used to forward motor commands controlling the body's position in space that take into account the environmental constraints [41,46].

Quiet standing is a motor-balance skill of everyday life that is automatically regulated by subcortical nervous structures and spinal-motoneuronal pools [30]. Although this is a rather simple postural task, it is now well established that quiet standing requires cognitive resources [31]. Minimal-attentional resources are needed in younger adults in an undisturbed upright stance, but in more challenging balance conditions (standing on a narrow support, balancing on one foot, walking on a difficult terrain), postural tasks are more cognitively demanding. An increased contribution of cortical structures, involved in motor attention (premotor cortex: [59]) and in the body's internal 3D representation (parietal lobe: [47,54,59,69]), is required when the postural tasks are complex or difficult and/or when the balance abilities of subjects are limited due to normal or pathological ageing.

Other postural behaviours encountered in everyday situations, however, are generally paired with cognitive performances. Indeed, it is the rule, rather than the exception, that individuals perform static- (standing) or dynamic- (walking) postural tasks simultaneously with cognitive tasks. Common real-word observations of people conversing while walking or listening to music while running illustrate this statement. In those situations, the attentional resources must be divided to properly perform both tasks. The question arises, therefore, as to whether dual-task conditions affect postural performance level. One way to answer this question is to compare the baseline-performance level recorded under a single-postural task condition without a concurrent cognitive task to postural performance under dual tasking. Dual-task costs have been reported [33] to result in a general decrease from single-task performance levels presumably because of competition for central processing resources. It has been clearly showed, however, that many variables can affect the performance level observed using the dual-task paradigm. Extrinsic factors depending on the nature of the primary task (such as static- or dynamic-postural tasks) or on the environmental context in which the task is performed (such as postural threat or not) as well as on the real nature of the secondary task (mental arithmetic, visual or spatial tasks) reportedly play a significant role [81]. Intrinsic factors depending on the subjects themselves — such as participants' sensorimotor expertise — have also been shown to affect the dual-task performance level [75]. Furthermore, the interpretation of dual-task data is rendered more difficult when taking into account empirical evidence that both sensorimotor [22,26,40] and cognitive [12,43] functions decline with life span. Undoubtedly, aging must modify the cross-talk between postural and cognitive tasks.

### Dual-task performance with aging

Falls in the old age constitute a serious public health problem because of their frequency (one third of adults, 65 years and over, falls at least one time per year: [60]) and of their dramatic consequences (femoral neck fracture: [70,71]). Post-fall syndrome also results in a combination of anxiety, fear of falling, and decreased mobility in the absence of training or physical activity [49].

Aging of the sensorimotor systems involved in posture control was believed to be the main cause of deterioration in balance abilities and of falls in the elderly [23,79]. A progressive decrease in visual acuity, contrast sensitivity and accommodation found in older adults is associated with increased-body sways during quiet standing [7]. A reduction of both vestibular and joint detection of body motion, reduced sensitivity of the plantar sole, and a diminished contribution of the proprioceptive muscular afferents to spinal reflexivity were reported in many clinical studies aimed at determining the effects of aging on the posture control system. Balance deterioration in old age is further accentuated by a lower muscle force in the antigravitary-extensor muscles [26], but a greater muscle activity during quiet standing [32], and by a diminution in the capacity of brain-stem centres controlling posture and gait to integrate the multisensory cues and to select appropriately the sensory information [80]. Moreover, age-related morphological and biochemical changes were shown in high-level integrative nervous structures, such as the parietal [72] and prefrontal [27] cortices, known for their contribution to the internal representation of the body in space and to attentional processes, respectively. Li and Lindenberger [34] suggested, therefore, that a greater cognitive demand could result after impairment of cortical areas responsible for sensorimotor processing of posture in older adults.

Balance control impairment and body instability in older adults resulting from deficits in the allocation of attention have been considered only recently [76,81]. Given the importance of dual-task performance for independent living in old age, this emerging-research area, relating attention and postural control, has recently come under intensive investigation. Consequently, there is no doubt today that older adults require greater cognitive resources than younger adults when performing the same postural tasks. Cognitively demanding tasks during walking, for instance, have a destabilizing effect on gait and may place older people at a greater risk of falling. Studies of the effects of divided attention on balance control consisted of comparing postural behaviours in subjects performing a concurrent cognitive task and differences with respect to the single postural-task baseline level were found with mental-arithmetic tasks [8,24], memory tasks [35,37], verbal tasks [28,42], reaction-time tasks [24,56,67] and spatial tasks [24,42-43]. In such divided attention situations, dual-task costs were greater in older adults than in younger adults, with only a few exceptions [33].

## Dual-task performance models

### Model 1: the cross-domain competition model

This model postulates that posture control and cognitive activity compete for attentional resources so that postural performance in dual-task conditions should be altered compared to the single postural-task performance. Because of attentional resource sharing, balance performance should be less efficient in dual-task conditions. Supporting this model is the observation of age differences in postural stability, increased by additional cognitive demands under quiet-standing conditions [42], and of postural stability decrement under more challenging postural conditions (standing on a sway-referenced platform) when performing a concurrent-visuospatial task [2]. More recent studies have confirmed this view. The negative effects on posture of this attentional resource competition are greater in older adults compared to younger adults as a result of diminished cognitive and attentional capacities in the elderly [48,53,62].

Other investigations, however, reported no change [61,83] or even an improvement [1,2,14,55,65,74] in postural control with the dual-task paradigm. These apparent discrepancies can be attributed to the difficulty of the postural task itself (undisturbed-quiet standing versus dynamic-postural perturbations) and/or to the type and complexity of the secondary task [81]. Taken together, these data point to serious limitations of this first model, in that it fails to account for all the data recorded in dual-tasking.

### Model 2: the U-shaped nonlinear interaction model

A more complex interaction between age and task characteristics has emerged recently from dual-task literature, which postulates a U-shaped relationship between posture control and cognitive demand. This conception means that body balance can be either improved or diminished depending on whether the cognitive demand of the secondary task is low or high.

Young subjects, standing quietly on a force platform, showed a decrease in postural sway when performing simultaneous reaction-time tasks consisting of verbal responses to visual or auditory stimuli [74]. Quality of postural control was also improved in older adults tested in similar postural conditions with cognitive load increased through rotatory-auditory stimulation [16]. The results suggest that balance improvement in dual-task conditions can be observed independently of age with low-demanding secondary-cognitive tasks. This may be due to a shift of the focus of attention away from posture control, increasing the automatic processing of posture [44,57,82]. In line with this is the observation that instructing participants explicitly to focus their attention on the postural control task itself leads to body-sway increase [73], due to the interference of the instructions on a highly automatic-control process [24]. The type of cognitive task (spatial versus nonspatial) as well as the cognitive processing required (encoding versus maintenance) can also differentially affect postural balance in dual-task conditions [43].

Using three different verbal-cognitive tasks, differing with regard to their levels of cognitive demand (choice-reaction time, digit, and spatial-working memory tasks), Huxhold et al. [24] showed that body sway increased in older adults under the more demanding cognitive tasks, whereas it was unchanged in younger adults. These results corroborated previous work [16,57,75] and support the hypothesis of a U-shaped relation between postural control and cognitive demand. With no correlation having been found between body-sway amplitude and level of arousal induced by the cognitive tasks, an arousal-based explanation for this nonlinear dual-task interaction was rejected [39]. The most relevant conclusion drawn from the work supporting this U-shaped dual-task interaction is that the level of cognitive demand, inducing a detrimental effect on posture control, was shifted to the low range in the older adults compared to the younger adults. In other words, the beneficial range of the cognitive task was reduced with aging, while the detrimental range was increased due to cross-domain resource competition (cf Model 1) and reduced attentional capacities in older adults.

In considering this model, however, one critical point must be emphasized: the aforementioned studies did not evaluate postural performance with similar parameters. While some investigators used the total-length path or surface of the stabilogram in subjects standing on a force platform, others examined body-sway velocity or the variance of their centre of foot pressure. Although all these traditional-postural parameters may quantify the postural performance, their functional relevance remains unevaluated and their limitations must be considered when comparing dual-task performances in younger and older adults (see Section ''Toward more functional describers of posture control for aging and dual-task investigations'' below).

### Model 3: the task prioritization model

It has been shown that the dynamics of balance control could be achieved differently among subjects, that is to say, by using different sensorimotor strategies. A good illustration is the description by Nashner [50] and Nashner and McCollum [51] of distinct ankle and hip strategies in humans standing on a force platform suddenly moved forward or backward. These strategies are underpinned by different spatiotemporal patterns of muscular activation, with the ankle strategy inducing a bottom-up activation pattern involving the gastrocnemius, hamstrings and paraspinal muscles, and the hip strategy showing a top-down pattern involving the abdominal and quadriceps femoris muscles. Interestingly, individuals are capable of shifting from one pattern to the other depending on the environmental context (wide-support surface versus narrow-support surface) or on their mental representation of the task difficulty (keeping balance on a wide-support surface placed on the ground versus above ground).

The hip strategy was reported to be predominantly used by the older adults. This suggests that the central representation of the postural task leads the brain to select the safer strategy to avoid falls. The hip strategy, which keeps the centre of gravity within the support surface, seems more highly prioritized with aging. In fact, whereas the ankle strategy is of low-energy cost and remains within the tolerance margins of the posture-control system for young adults, the hip strategy is more energetically demanding, but safer, for older adults. Patients with vestibular loss also exhibited the hip strategy, very likely for similar reasons.

The empirical observation that elderly people stop walking when they start a conversation with a walking companion is another illustration of this concept of aging-induced strategies to avoid fall. Because decreased-cognitive resources correspond to decreased dual-task performance, doing two things at once becomes more difficult and in some cases, the elderly stop walking when talking. This simple observation has been proposed as a clinical test for prediction of fall in elderly people [38]. Compared to younger adults, older adults prioritize postural control in divided attention situations, particularly in the case of frail-elderly individuals with balance problems for whom avoiding fall is of critical-survival value. Additionally, a greater number of older than younger adults prioritize postural control over cognitive-task performance under conditions of increased-postural threat [9].

Within this same conceptual frame of task prioritization is the ''posture first'' principle, which has been proposed as an explanation for cognitive-task deterioration as a consequence of balance prioritization in dual-task conditions where age is a prominent factor [61] and environmental context is a modulating factor in older adults [9]. Along this same line is the ecological approach to multitasking [34—36], a concept inspired by the Baltes' model of selection, optimization, and compensation (SOC: [3]). The SOC model [33] is based on:

- the selection of the goals that are crucial for the individual;
- the optimization of the performance level of the selected goal by all relevant means;
- the compensation principle, that is, the use of alternative strategies for maintaining the performance level.

This model takes into account the adaptive responses to age-related declines that lead to compensatory behaviours or strategies like task prioritization. Its main prediction is that older adults prioritize postural stability and balance at the expense of the cognitive performance in dual tasking. Indeed, most dual-tasking investigations show that older adults allocate resources to posture control at a cost to cognitive performance, that is, they select the domain they consider more important to them, particularly when postural-task complexity is increased [9,31,35,37,66,68]. Some reports in the literature, however, contradict this prediction, with some age-related increases of cognitive involvement in posture control reported [43,61]. Such discrepancies may also be attributable to the environmental context or to the type and complexity of the postural and cognitive tasks.

Prioritization of posture control in older adults can be seen as a compensatory reallocation of attention [33] and fit into the conceptual frame of brain plasticity as a behavioural plasticity mechanism rather than as a decline in cognitive capacities. Similar adaptive processes have been described for both age-related declines in the elderly and lesion-induced deficits of the sensory and motor systems in vestibular-defective patients [29].

## Toward more functional describers of posture control for aging and dual-task investigations

How to go about investigating posture control is not a trivial question: the evaluation of shared attentional resources on postural stability with aging is strongly dependent on the describers of posture control. Balance performance can be measured using kinematic or dynamic approaches for the purpose of motion analysis or force quantification, respectively. The dynamic approach, using a stable force platform, has predominantly been used in clinical investigations, since it is a relatively simple and low-cost technique, well adapted for testing pathological as well as elderly subjects in a relatively short-time period. The electromyography method, as well as techniques based on motion analysis or accelerometer recordings, on the other hand, are better suited to laboratory conditions than to routine-clinical investigations.

With a subject standing quietly on a stable support, one substantial challenge is to record signals that are effective in describing static-balance control and to interpret these signals in terms of postural performance or strategy. A similar challenge arises in the investigation of posture control under dynamic-postural conditions [77]. In both cases, the posturography method quantifies the reaction forces of the support: the force platform provides the vertical bottom-up forces counteracting the top-down forces, resulting from the gravity vector and the reaction-muscular forces.

## Limitations of the traditional describers of posture control

In a rather simple postural task (quiet standing), the organization of human posture can be referred to the inverted pendulum model and balance control is considered to be achieved properly when the projection of the centre of mass remains within the support surface [41,64]. This simplified view does not necessarily fit real-postural behaviour, though, since the postural system is composed of the superposition of different jointed modules from feet to head, each of which can be controlled independently [21]. For instance, Nashner [50] described two strategies of head stabilization: the ''strap-down'' strategy that stabilizes head on trunk and the ''stable-platform'' strategy that stabilizes head on space. Multi-jointed posture-control strategies in the sagittal plane have also been described with altered support-surface configurations [50,51]. According to the inverted pendulum model, the ankle strategy induces AP displacements of the centre of mass, which result in significant AP displacements of its vertical projection: the centre of foot pressure (CoP). By contrast, the hip strategy associates ankle plantar flexion and hip flexion (or ankle-dorsal flexion and hip extension) that tend to minimize the CoP displacements.

Consequently, the assumption that CoP displacement is a good proxy for the postural performance can lead to misevaluations of the quality of the balance-control system tested under static or dynamic conditions. Increased or decreased CoP displacements, recorded in subjects performing postural tasks, can reveal age-related strategies or context-dependent behaviours rather than worse or better postural performances, respectively. In most dual-task studies, however, balance performance of younger versus older adults was assessed by quantifying the CoP displacements in subjects standing on a stable force platform. Brown et al. [9] quantified postural performance using this parameter and showed improvement of postural stability in their older participants because their CoP area decreased as postural threat increased, whereas no changes were reported for younger adults. Decrease in CoP area can result from a better integration of the multisensory inputs controlling posture and underpin the improvement of posture control. But similar CoP changes can result from an increased-body stiffness associated with fear of falling. Brown et al. demonstrated a prioritization of posture control over cognitive performance or, rather, a strategy, primarily, to avoid fall. This example, then, demonstrates the limitations of traditional-posturography method and the need for other mathematical and statistical tools to describe postural performance.

## New describers of posture control

### The stabilogram-diffusion analysis

The stabilogram-diffusion analysis elaborated by Collins and De Luca [10] is based on fundamental concepts and principles from statistical-mechanics. Einstein [19] studied Brownian motion (an example of a statistical mechanics phenomenon) and demonstrated that the mean-square displacement of a one-dimensional random walk of a single particle is linearly related to the time interval. In stabilogram-diffusion analysis, the displacement analysis of CoP trajectories is carried out according to fractional Brownian-motion analysis (a Gaussian stochastic process) and the mean square CoP planar displacement ($\Delta r^2$) is plotted as a function of time interval ($\Delta t$: a moving time window) for a CoP trajectory made of $N$ data points. The stabilogram-diffusion plot exhibits two regions (the short-term and long-term regions), distinguishable on the basis of the coordinates of the critical point defined by the intersection of the regression lines fitted to these two regions. This method is interesting for its capacity to extract CoP parameters that can be directly related to the steady-state behaviour and functional interaction of the neuromuscular mechanisms underlying the maintenance of upright stance. Collins and De Luca [10] suggest, from a physiological point of view, that the critical point coordinates approximate the temporal and spatial characteristics of the region over which the posture control switches from open-loop to closed-loop control mechanisms. This hypothesis is particularly relevant for studies investigating posture control, aging and dual tasking. Other methods, based on the modelling of CoP trajectories by fractional-Brownian motion, have followed these earlier ones [58].

Collins et al. [11] detected no age-related effects on posture control during quiet standing with the more traditional-posturographic analyses, but these methods were not sensitive enough to differentiate between young (aged 19—30 years) and older (aged 71—80 years) adults, free of gait and postural deficits. Interestingly, they described age-related changes in the open-loop and closed-loop postural-control mechanisms, that is, changes with aging in the dynamics of the posture control system. The stabilogram-diffusion plots, recorded in elderly participants, showed significant increases in their critical-mean square displacement and critical time interval (Fig. 1). These data strongly suggest that older adults utilize open-loop control mechanisms for longer time intervals and call into play closed-loop feedback mechanisms with a greater delay compared to younger adults. Such changes in the temporal interaction of open-loop and closed-loop control mechanisms are supported by observations of increased reflex time [25], reduced proprioception [63] and weaker muscle strength [26], reported as common consequences of the aging process. Aging-induced increases in time to initiate corrective processes have also been demonstrated in the mediolateral axis in seniors compared to younger adults [5]. Changes in the spatial characteristics of open-loop postural-control mechanisms are also consistent with the postural strategy adopted by elderly individuals, which consists of increasing muscular stiffness caused by a coactivation of the lower-limb muscles. Stiffness control of balance during quiet standing can be due to increased frequency and decreased amplitude of sway if the body is modelled as an inverted pendulum [58,78]. It is, furthermore, noteworthy that increased stiffness has been reported in both young-healthy adults [15] and older adults [45] in dual-task paradigms, for instance when a concurrent attention task was performed simultaneously with a postural task. As reported by Benjuya et al. [4], using static posturography and EMG recordings, elderly individuals seem to have developed a strategy of stiffening and freezing their lower legs during upright standing. According to the SOC model, this could be an aging-induced compensatory strategy that shifts posture control from a

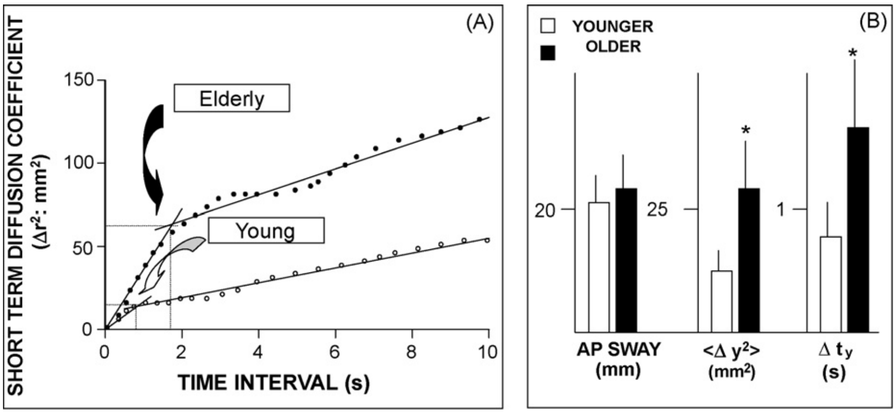

**Figure 1** A—B. Stabilogram-diffusion analysis. A. Linear—linear plots of mean-square CoP displacement versus time interval. Planar stabilogram-diffusion plots and fitted regression lines are illustrated for two representative healthy subjects, one young adult (20 years) and one older adult (71 years). The critical point is shown for each subject as the intersection of the two regression lines performed on the raw CoP displacement data. It provides the critical-time interval (in seconds: on the abscissae) and the critical-mean square displacement (in square millimetres: on the ordinates) that are both increased in the older adult compared to the younger. The short-term and long-term diffusion coefficients can be calculated from the slope of the fitted regression lines for the mediolateral (ML), anteroposterior (AP) or coplanar CoP displacements. B. Comparison of the traditional-postural parameters with the stabilogram-diffusion analysis. The AP sway does not differentiate the two groups of healthy young and older subjects (neither the total-sway path nor the sway area, ML path or radial area). By contrast, the critical-time interval ($\Delta t_y$) and mean-square displacement ($\Delta y^2$) in the AP direction (as well as in the ML direction and for planar CoP displacements) show significant differences (*: $p < 0.001$) between the two groups. Modified from [10].

reliance on sensory inputs to coactivation of antagonistic muscles. Such a strategy is consistent with temporal changes in the open-loop control mechanism observed in older adults, since this mechanism operates without sensory feedback and corresponds to descending commands [32].

## Wavelet analysis

The stabilogram-diffusion analysis and fractional-Brownian modelling are significant attempts at improving our understanding of posture control. The wavelet transform is another method that can be used to extract more useful information from the raw data provided by the CoP displacements.

One widely accepted idea in the field is that frequency contain of body sway can give some hints about the physiological processes underlying the maintenance of upright stance. Historically, one of the earliest attempts applied a Fourier transform to the recordings and, thus, gave insight about the main frequency components involved in the process of upright body stabilization. The fast-Fourier transform (FFT) provides the spectral power of body stabilization as information supplementary to the basic 2D coordinates of the CoP displacements, but the FFT has some major limitations: the spectral power precision in the low-frequency range is constrained by the duration of the recording and in the high-frequency range by the recordings' sampling frequency. In addition, due to body inertia, FFT-spectral power is shifted toward the low-frequency range, where very large body oscillations are found compared to the high-frequency range, where only small oscillations are present. And finally, the FFT lacks time resolution and may provide a false image of body sway-frequency content (Fig. 2).

A new conceptual framework we have developed [6,17—18], consists of describing body-sway frequencies as a function of time by applying the wavelet-transform method [13] to CoP displacements. In contrast to the Fourier transform, the wavelet transform considers the input signal to be composed of summed-elementary wavelets, which are in fact time-limited waveforms, that is, waves whose amplitude tends to zero at defined limits. The wavelets are also scalable, which is to say the amplitude and time window may be adjusted to best fit the original signal. Various waveforms (mother wavelets) have been used in a wide range of research domains, from oil-field localisation to prevention of heart attacks with electrocardiography-signal analysis. This method was also applied for the processing of electroencephalographic data and it succeeded in demonstrating the synchronous activation of brain-neuronal networks. Applied to CoP displacements, the wavelet transform elaborates a time-frequency chart of body sway and provides the first 3D representation of body sway available for investigating balance control under static or dynamic conditions. These wavelet plots show the frequencies of CoP displacement in the mediolateral or anteroposterior planes (on the ordinates) as a function of time (on the abscissae). The third dimension is provided by the colour code: cold colours are indicative of low amplitude-spectral powers, whereas hot colours point to high amplitude-spectral powers. Fig. 2 illustrates the advantage of this method compared to the FFT.

Assuming that a low frequency-optokinetic stimulation (0.1 Hz) has a destabilizing effect on posture [52], one can quantify the spectral-power density of body sway at this particular 0.1 Hz frequency or in the whole frequency range (0—0.5 Hz) corresponding to the visual contribution of vision to posture control. The spectral power can be also evaluated in the different frequency bands, characterizing the predominant functional domains of the various sensory inputs controlling posture (vision, muscular and vestibular propri-

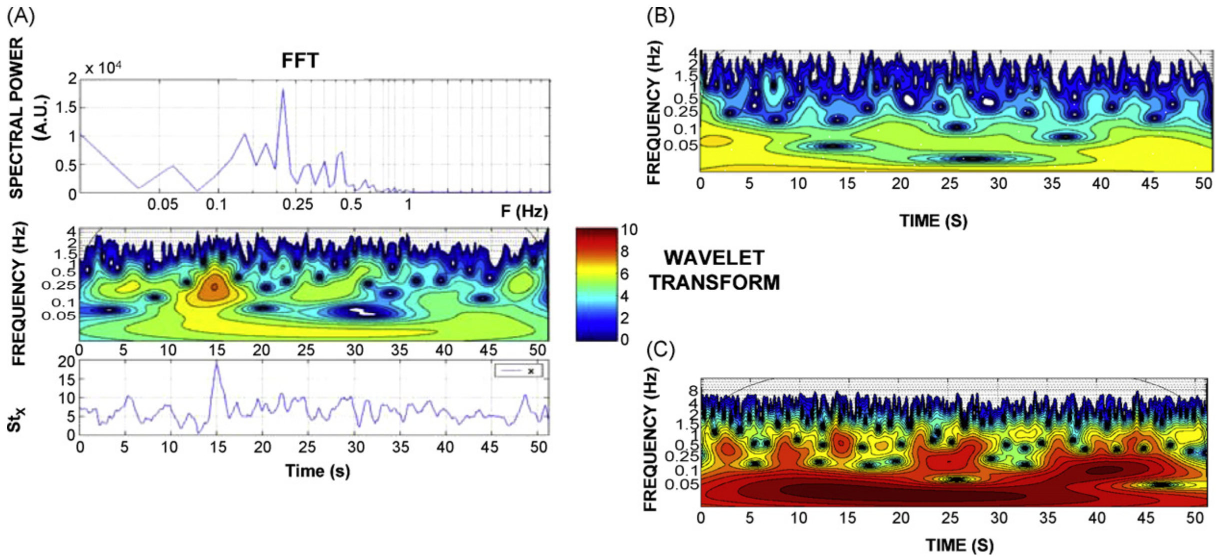

**Figure 2** A—C. Wavelet transform. Illustration of the wavelet analysis applied to the stabilogram of subjects standing quietly on a force platform without concurrent cognitive task. A. The wavelet transform, here applied on the CoP displacements in the mediolateral direction ($St_x$, lower panel) provides a 3D chart of lateral-body sway (middle panel) with time on the abscissae (in seconds), the frequency content of the stabilogram on the ordinates (in hertz), and the spectral power shown with a colour code for the third dimension. Result of the fast-Fourier transform (FFT: upper graph) is given for comparison. The FFT shows a fundamental peak at 0.23 Hz, while the wavelet transform shows a powerful body sway at this frequency occurring only around 15 s after the beginning of the recording and lasting only a few seconds. Considering the posture-control mechanisms, this peak has no physiological meaning since it corresponds to a brief voluntary change of lateral-body position [18]. B. 3D chart of the anteroposterior sway of a healthy-elderly adult tested in the eyes open condition. Note the predominance of cold colours in the low- (0.05 Hz—0.5 Hz) and middle- (0.5 Hz-1.5 Hz) frequency ranges and the quasi-absence of high frequencies, suggesting a very good posture control. C. 3D chart of the anteroposterior sway of a patient with a central pathology (multiple sclerosis) tested with his eyes open. Note the hot colours in both the low- and middle-frequency ranges, indicative of a poor-postural performance and the presence of very high frequencies (up to 6 Hz) neither encountered in normal subjects [17].

oception). The 3D charts are capable to show artifact-like events occurring during the recording session (Fig. 2A), postural strategies (increased high frequency-spectral power in subjects stiffening their ankle joint) and spectral-power densities typical of postural pathologies. Fig. 2B illustrates the 3D chart of a subject with a good postural stability. It was recorded in a healthy elderly, well trained physically and intellectually. Fig. 2C shows the 3D chart of a patient with a multiple sclerosis. One can see high frequencies (up to 6 Hz), never observed in normal subjects and not found with the FFT, and spectral powers of very high amplitude in the low-frequency range (hot colours), characterizing a very bad postural stability. Comparison of the frequency-power distribution in different groups or conditions can therefore be useful for testing age effects, pathologic states or environmental variations. Other parameters can be extracted with the wavelet transform as well, such as a postural-instability index quantifying the postural performance [6,17—18].

Taken together, the stabilogram-diffusion analysis and the wavelet analysis should provide more relevant information on posture control than the more traditional methods. These two methods have been incorporated in software we have developed (PosturoPro; Framiral, Cannes, France). Following is a comparison between the results obtained using traditional-postural parameters and those obtained with these new methods, in young versus older adults under dual-task conditions.

## Advantages of more functional describers of posture control over traditional posturography: illustration with the dual-task paradigm

Our dual-task paradigm used a crossed design, including both a static- (quiet standing) and a more challenging dynamic- (keeping balance on a translational platform) postural task and cognitive tasks with low- (silent-mental arithmetic) and with higher- (spatial-memory task) attentional loads [6]. One group of healthy-younger adults (23.4 years) and one group of healthy-older adults (75.6 years) matched with respect to their educational level, physical and intellectual activities were examined.

Fig. 3 illustrates the main results, recorded in groups of younger and older adults under the less challenging-postural task (quiet standing) in the reference condition (without cognitive task) and in the dual-task condition with the mental-arithmetic task or the spatial-memory task. In the reference condition, data processing with traditional-postural parameters (CoP length or area, CoP displacement in the ML or AP directions, body-sway velocity) remained unable to differentiate the two populations (Fig. 3A). Similar findings were observed with the stabilogram-diffusion analysis as no significant differences were found between the younger adults and the older adults with the short-term diffusion coefficient (Fig. 3B). The critical-time interval as well as the critical-mean square again showed no significant differences. Furthermore, the wavelet transform did not point

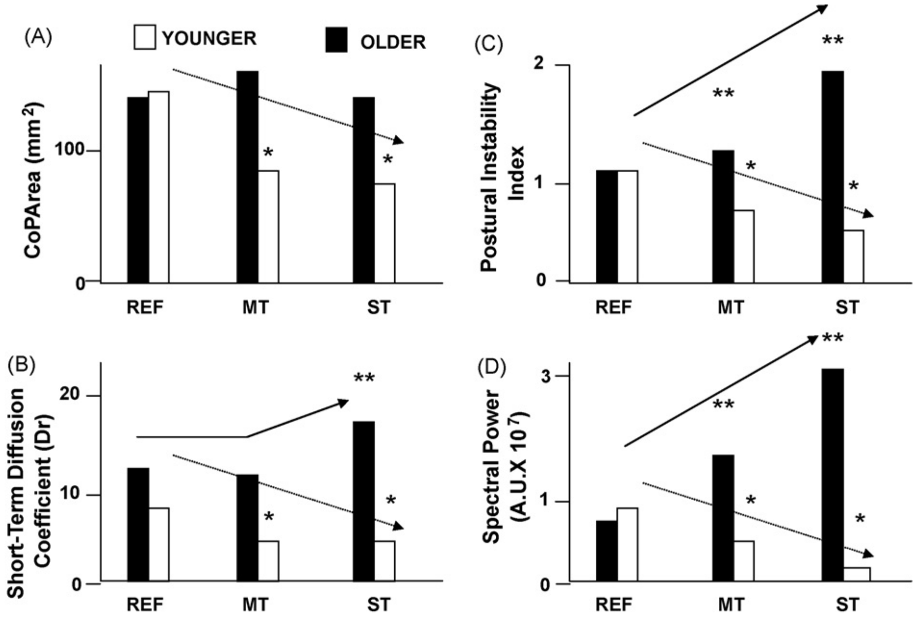

**Figure 3** A—D. Advantages of the stabilogram-diffusion and wavelet-transform analyses over the traditional-posturographic method. Mean results recorded in two populations of young- and older-healthy subjects standing quietly on a force platform without concurrent cognitive task (REF) and in dual tasking with a mental-arithmetic task (MT) or a spatial-memory task (ST). A. Group mean for the younger (open histograms) and the older (filled histograms) adults for the CoP area parameter (confident ellipse containing 90% of the sampling points: in square millimetres). B. Group means for the short-term diffusion coefficient provided by the stabilogram-diffusion analysis. (C—D). Group means for two parameters elaborated from the wavelet transform — the postural-instability index (C) and the spectral power calculated in the 0.5—1.5 Hz-frequency range (D: expressed in arbitrary units × $10^7$). Note the absence of effects of dual tasking on posture control in the older group with the traditional-posturographic analysis, not sensitive enough to detect attentional load-induced effects, whereas the stabilogram-diffusion and the wavelet-transform methods show significant differences. * and ** indicate significant differences ($p < 0.01$) between the postural performance under dual-task situation and the reference for the younger adults and the older adults, respectively. The solid and dashed arrows illustrate the changes in the postural performance examined in the REF, MT and ST conditions in the younger and older groups, respectively. Modified from [6].

to statistical differences between the two groups (Fig. 3C and D). Taken together, these results show that the postural performance during quiet standing is similar in younger and older adults, a result that could be predicted on the basis of the selection criteria for cognitively and physically healthy-elderly subjects.

The addition of a concurrent cognitive task was particularly interesting in this static situation where posture-control mechanisms appeared unmodified in the elderly group compared to the younger group. The older adults showed no significant change of their posture performance, either with the arithmetic or the spatial task when measured by CoP area or other traditional parameters (Fig. 3A). In contrast, significant changes were observed with the new methods in the elderly group during dual tasking. The short-term diffusion coefficient (stabilogram-diffusion analysis: Fig. 3B), the postural-instability index and the spectral power (wavelet transform: Fig. 3C and D, respectively) were each strongly increased compared to the reference condition. Additionally, the higher the cognitive demand (spatial task versus arithmetic task), the greater the increase in these parameters. Interestingly, a completely opposite pattern was observed in younger adults, with sharply-decreased values when a concurrent cognitive task was performed simultaneously. The higher the cognitive load, the greater the decrease.

## Concluding remarks

The results reported in this multidimensional approach of posture control clearly show that:

- normal aging does not lead ineluctably to changes in posture control. Selected healthy-elderly subjects undergoing a daily physical-activity routine show a postural performance similar to that of younger adults — not only is their postural stability as judged by their CoP displacements not altered, but they seem to be controlling their posture using similar mechanisms and strategies. Indeed, the dynamics of their open-loop and closed-loop postural-control mechanisms as well as the whole spectral content of their body sway are not distinguishable from those of younger adults. The benefits of regular physical and cognitive activities in helping to promote independent living and to avoid fall in old age is clearly evidenced here;
- traditional-posturographic analyses are not sensitive enough to detect age-related differences under dual-task conditions, a conclusion already drawn by others [11,20]. In contrast, the stabilogram-diffusion analysis and the wavelet transform provide congruent and more functional insight into the effects of dual tasking, even in the case of a very simple postural task (quiet standing);

- dual tasking leads to postural performance improvement in younger adults where performance decreases are seen in older adults. Balance improvement in younger subjects very likely reflects a shift in attention away from posture control that automates the processing of posture [24,44,57,73,82]. The strongest effect between the spatial memory task and the arithmetic task can be seen as the result of higher cognitive demand, leading to greater automation of processing [43]. Balance alteration in the older adults could be explained by the cross-domain competition model if one considers only the dual-task paradigm performed with the simple quiet standing-postural task reported herein. Our protocol was not aimed at testing the U-shaped interaction model since it included only two different cognitive tasks, but it was well adapted to evaluate the task prioritization model because postural tasks of increased difficulty were used. The results (not reported here: see [6]) support this conclusion and show that the ''posture first'' principle, described in elderly people during dual tasking [61], is very likely achieved in our healthy-older adults by a compensatory attention reallocation and a stiffening strategy in accordance with previous findings [4] and the SOC model [32].

## Conflicts of interest

None.

## References

[1] Andersson G, Hagman J, Talianzadeh R, Svedberg A, Larsen HC. Effect of cognitive load on postural control. Brain Res Bull 2002;58:135—9.

[2] Andersson G, Yardley L, Luxon L. A dual task study of interference between mental activity and control of balance. Am J Otolaryngol 1998;19:632—7.

[3] Baltes PB, Baltes MM. Psychological perspectives on successful aging:the model of selective optimization with compensation. In: Baltes PB, Baltes MM, editors. Successful aging: perspectives from the behavioural sciences. Cambridge, New York: Cambridge University Press; 1990. p. 1—34.

[4] Benjuya N, Melzer I, Kaplanski J. Aging-induced shifts from a reliance on sensory input to muscle cocontraction during balanced standing. J Gerontol A Biol Med Sci 2004;59: 166—71.

[5] Berger L, Chuzel M, Buisson G, Rougier P. Undisturbed upright stance control in the elderly: I. Age-related changes in undisturbed upright stance control. J Mot Behav 2005;37: 348—58.

[6] Bernard L, Jimeno P, Borel L, Dumitrescu M, Lacour M. Age-related differences in human posture control are differentially affected by postural and cognitive tasks complexity. Gerontol (in revision).

[7] Bohannon R, Larkin PA, Cook AC, Gear J, Singer J. Decrease in timed balance test scores with ageing. Phys Ther 1984;64:1067—70.

[8] Brown LA, Shumway-Cook A, Woollacott MH. Attentional demands and postural recovery: the effects of aging. J Gerontol 1999;54A:M165—71.

[9] Brown LA, Sleik RJ, Polych MA, Gage WH. Is the prioritization of postural control altered in conditions of postural threat in younger and older adults? J Gerontol Med Sci 2002;57A:M785—92.

[10] Collins JJ, De Luca CJ. Open-loop and closed-loop control of posture: a random-walk analysis of center-of-pressure trajectories. Exp Brain Res 1993;95:308—18.

[11] Collins JJ, De Luca CJ, Burrows A, Lipsitz LA. Age-related changes in open-loop and closed-loop postural control mechanisms. Exp Brain Res 1995;104:480—92.

[12] Craik FIM, Salthouse TA. The handbook of aging and cognition. 2nd ed Mahwah NJ: Lawrence Erlbaum Associates; 2000.

[13] Daubechies I. The wavelet transform: a method for time-frequency localization. In: Haykin, editor. Advances in spectrum analysis and array processing, 1. Prentice-Hall; 1991. p. 366—417.

[14] Dault MC, Geurts AC, Mulder TW, Duysens J. Postural control and cognitive task performance in healthy participants while balancing on different support-surface configuration. Gait Posture 2001;14:248—55.

[15] Dault MC, Yardley L, Frank JS. Does articulation contribute to modifications of postural control during dual-task paradigms? Cogn Brain Res 2003;16:434—40.

[16] Deviterne D, Gauchard GC, Jamet M, Vancon G, Perrin PP. Added cognitive load through rotatory auditory stimulation can improve the quality of postural control in the elderly. Brain Res Bull 2005;64:487—92.

[17] Dumitrescu MP, Lacour M. Analyse mathématique par décomposition en ondelettes des signaux stabilométriques. In: Lacour M, editor. Nouvelles méthodes de traitement du signal stabilométrique. Marseille: Solal; 2004. p. 13—24.

[18] Dumitrescu MP, Lacour M. Nouveaux critères quantitatifs d'analyse du contrôle postural : illustrations en pathologie et chez la personne âgée. In: Pérennou D, Lacour M, editors. Efficience et déficiences du contrôle postural. Marseille: Solal; 2006. p. 65—75.

[19] Einstein A. Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen. Ann Phys 1905;322:549—60.

[20] Ghulyan V, Paolino M, Lopez C, Dumitrescu M, Lacour M. A new translational platform for evaluating aging and pathology-related postural disorders. Acta Otolaryngol 2005;125: 607—17.

[21] Gurfinkel VS, Lipshits MI, Popov KE. Stabilization of the body position as the main task of postural regulation. Fiziologya Cheloveka 1981;7:400—10.

[22] Horak FB, Nashner LM. Central programming of postural movements: adaptation to altered support-surface configurations. J Neurophysiol 1986;55(6):1369—81.

[23] Horak FB, Shupert CL, Mirka A. Components of postural dyscontrol in the elderly: a review. Neurobiol Aging 1989;10: 727—38.

[24] Huxhold O, Li SC, Schmiedek F, Lindenberger U. Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention. Brain Res Bull 2006;69:294—305.

[25] Inglin B, Woollacott M. Age-related changes in anticipatory postural adjustments associated with arm movements. J Gerontol 1988;43:M105—13.

[26] Jette AM, Branch LG, Berlin J. Musculoskeletal impairments and physical disablement among the aged. J Gerontol Med Sci 1990;45:M203—8.

[27] Johnson MK, Mitchel KJ, Raye CL, Green EJ. An age-related deficit in prefrontal cortical function associated with refreshing information. Psychol Sci 2004;15:127—32.

[28] Kerr B, Condon SM, Mcdonald LA. Cognitive spatial processing and the regulation of posture. J Exp Psychol 1985;11(5):617—22.

[29] Lacour M. Restoration of vestibular functions: basic aspects and practical advances for rehabilitation. Curr Med Res Opin 2006;22:1651—9.

[30] Lacour M, Borel L. Vestibular control of posture and gait. Arch Ital Biol 1993;131:81—104.

[31] Lajoie Y, Teasdale N, Bard C, Fleury M. Attentional demands for static and dynamic equilibrium. Exp Brain Res 1993;97: 139—44.

[32] Laughton CA, Slavin M, Katdare K, Nolan N, Bean JF, Kerrigan DC, et al. Aging, muscle activity, and balance control: physiologic changes associated with balance impairment. Gait Posture 2004;18:101—18.

[33] Li KZH, Krampe RTh, Bondar A. An ecological approach to studying aging and dual-task performance. In: Engle RW, Sedek G, von Hecker U, McIntosh DN, editors. Cognitive limitations in aging and psychopathology. Cambridge University Press; 2005. p. 190—218.

[34] Li KZH, Lindenberger U. Relations between aging sensory/sensorimotor and cognitive functions. Neurosci Biobeh Rev 2002;26:777—83.

[35] Li KZH, Lindenberger U, Freund AM, Baltes PB. Walking while memorizing: age-related differences in compensatory behaviour. Psychol Sci 2001;12:230—7.

[36] Lindenberger U, Baltes PB. Intellectual functioning in old and very old age: cross-sectional results from the Berlin Aging Study. Psychol Aging 2000;12:410—32.

[37] Lindenberger U, Marsiske M, Baltes PB. Memorizing while walking: increase in dual-task costs from young adulthood to old age. Psychol Aging 2000;15(3):417—36.

[38] Lundin-Olsson N, Nyberg L, Gustafson Y. Stops walking when talking as a predictor of falls in elderly people. Lancet 1997;349:617.

[39] Maki BE, McIlroy WE. Influence of arousal and attention on the control of postural sway. J Vest Res 1996;6:53—9.

[40] Manchester D, Woollacott M, Zederbauer-Hylton N, Marin O. Visual, vestibular and somatosensoty contributions to balance control in the older adult. J Gerontol 1989;44:M118—27.

[41] Massion J. Postural control system. Curr Opin Neurobiol 1994;4:877—87.

[42] Maylor EA, Wing AM. Age differences in postural stability are increased by additional cognitive demands. J Gerontol Psychol Sci 1996;51:143—54.

[43] Maylor EA, Allison S, Wing AM. Effects of spatial and nonspatial cognitive activity on postural stability. Br J Psychol 2001;92:319—38.

[44] McNevin NH, Wulf G. Attentional focus on supra-postural tasks affects postural control. Hum Mov Sci 2002;21(2):187—202.

[45] Melzer I, Benjuya N, Kaplanski J. Age-related changes of postural control: effect of cognitive tasks. Gerontology 2001;47:189—94.

[46] Mergner T, Rosemeier T. Interaction of vestibular, somatosensory and visual signals for postural control under terrestrial and micrgravity conditions: a conceptual model. Brain Res Rev 1998:118—35.

[47] Michel C, Rosseti Y, Rode G, Tilikete C. After-effects of visuo-manual adaptation to prisms on body posture in normal subjects. Exp Brain Res 2003;148:219—26.

[48] Mitra S. Postural cost of suprapostural task load. Hum Mov Sci 2003;22:253—70.

[49] Murphy J, Isaacs B. The post-fall syndrome. Gerontology 1980;49:265—70.

[50] Nashner LM. Strategies for organization of human posture. In: Igarashi M, Black FO, editors. Vestibular and visual control of posture and locomotor equilibrium. Basel: Karger; 1985. p. 1—8.

[51] Nashner LM, McCollum. The organization of human postural movements: a formal basis and experimental synthesis. Behav Brain Sci 1985;8:135—72.

[52] Paulus WM, Straube A, Brandt T. Visual stabilization of posture: physiological stimulus characteristics and clinical aspects. Brain 1984;107:1143—63.

[53] Pellecchia G. Postural sway increases with attentional demands of concurrent cognitive task. Gait Posture 2003;18:29—34.

[54] Pérennou DA, Leblond C, Amblard N, Micallef JP, Hérisson C, Pélissier JY. Transcutaneous electric nerve stimulation reduces neglect-related postural instability after stroke. Arch Phys Med Rehabil 2001;82:440—7.

[55] Prado JN, Stoffregen TA, Duarte M. Postural sway during dual-tasks in young and elderly adults. Gerontology 2007;53:274—81.

[56] Redfern MS, Jennings JR, Martin C, Furman JM. Attention influences sensory integration for postural control in older adults. Gait Posture 2001;14:211—6.

[57] Riley MA, Baker AA, Schmit JM. Inverse relation between postural variability and difficulty of a concurrent short-term memory task. Brain Res Bull 2003;62:191—5.

[58] Rougier P, Caron O. Center of gravity motions and ankle joint stiffness control in upright undisturbed stance modelled through fractional Brownian motion framework. J Mot Behav 2000;32:405—13.

[59] Rushworth MFS, Johansen-Berg H, Göbel SM, Devlin JT. The left parietal and premotor cortices: motor attention and selection. NeuroImage 2003;20:S89—100.

[60] Sattin RW. Falls among older persons: a public health perspective. Ann Rev Pub Health 1992;13:489—508.

[61] Shumway-Cook A, Woollacott M, Kerns KA, Baldwin M. The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. J Gerontol A Biol Sci Med Sci 1997;52:M232—40.

[62] Shumway-Cook A, Woollacott M. Attentional demands and postural control: the effect of sensory context. J Gerontol Biol Sci 2000;55A:M10—6.

[63] Skinner HB, Barrack RL, Cook SD. Age-related decline in proprioception. Clin Orthop 1984;184:208—11.

[64] Sparrow WA, Hughes KM, Russell AP, Le Rossignol PF. Movement economy, preferred modes, and pacing. In: Sparrow WA, editor. Energetics of human activity. Champaign (Il): Human Kinetics; 2000. p. 96—123.

[65] Swan L, Otani H, Loubert P, Sheffer SM, Dunbar GL. Improving balance by performing a secondary cognitive task. Br J Psychol 2004;95:31—40.

[66] Teasdale N, Bard C, Dadouchi F, Fleury M, LaRue J, Stelmach GE. Posture and elderly persons: evidence for deficits in the central integrative mechanisms. In: Stelmach GE, Requin J, editors. Tutorials in motor behaviour II. Amsterdam: Elsevier Science; 1992. p. 917—31.

[67] Teasdale N, Simoneau M. Attentional demands for postural control: the effects of aging and sensory reintegration. Gait Posture 2001;14:203—10.

[68] Teasdale N, Bard C, Larue J, Fleury M. On the cognitive penetrability of posture control. Exp Aging Res 1993;19:1—13.

[69] Their P, Karnath PO. Parietal lobe contribution to orientation in 3D space. Heidelberg: Springer-Verlag; 1997.

[70] Tinetti ME. Performed oriented assessment of mobility problems in the elderly. J Am Geriat Soc 1986;36:613—6.

[71] Tinetti ME. Falls. In: Hazzard WR, Bierman EL, Blass JP, Ettinger WH, Halter JB, editors. Principles of geriatric medicine and gerontology. 3rd ed New York: McGraw-Hill; 1995.

[72] Tisserand DJ, van Boxtel MPJ, Pruessner JC, Hofman P, Evans AC, Joilles J. A voxel-based morphometric study to determine individual differences in gray matter density associated with age and cognitive change over time. Cereb Cortex 2004;14:966—1013.

[73] Vuillerme N, Nafati G. How attentional focus on body sway affects postural control during quiet standing. Psychol Res 2005;71(2):192—200.

[74] Vuillerme N, Nougier V, Teasdale N. Effects of a reaction time task on postural control in humans. Neurosci Lett 2000;291:77—80.

[75] Vuillerme N, Nougier V. Attentional demand for postural sway: the effect of expertise in gymnastics. Brain Res Bull 2004;63:161—5.

[76] Weeks DL, Forget R, Mouchnino L, Gravel D, Bourbonnais D. Interaction between attention demanding motor and cognitive tasks and static postural stability. Gerontology 2003;49:225—32.

[77] Winter DA. Human balance and posture control during standing and walking. Gait Posture 1995;3:193—214.

[78] Winter DA, Patla AE, Prince F, Ishac M, Gielo-Perczak K. Stiffness control of balance in quiet standing. J Neurophysiol 1998;80:1211—21.

[79] Woollacott M. Systems contributing to balance disorders in older adults. J Gerontol Med Sci 2000;55A:M424—8.

[80] Woollacott M, Shumway-Cook A, Nashner LM. Aging and posture control: changes in sensory organization and muscular coordination. Int J Aging Hum Dev 1986;23:97—114.

[81] Woollacott M, Shumway-Cook A. Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture 2002;16:1—14.

[82] Wulf G, Mercer J, McNevin N, Guadagnoli MA. Reciprocal influences of attentional focus on postural and suprapostural task performance. J Mot Behav 2004;36(2):189—99.

[83] Yardley L, Gardener M, Bronstein A, Davies R, Buckwell D, Luxon L. Interference between postural control and mental task performance in patients with vestibular disorders and healthy controls. J Neurol Neurosurg Psychiatry 2001;71:48—52.