Haptic supplementation and postural control in the elderly: Review and perspectives for assistive technologies

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Abstract. The present review paper focuses on the potential beneficial effect of haptic supplementation on postural control in the elderly. In the first part, we analyse the effects of age-related alterations in sensory integration on postural stability, in relation with the current models of human upright stance and sensorimotor mechanisms of postural control. Then, we present existing biofeedback devices and the most influential studies on haptic supplementation provided by a fixed or a mobile “touch support” that have been shown to enhance postural stability. In particular, we detailed preliminary results of a research program currently in progress in our group to investigate the effect of functional haptic information provided by a mobile support on postural stability. We speculate about potential applications of these findings. Finally, we suggest that investigating the effects of a haptic stick could help to better understand how elderly people use a walking aid in a “light” manner as a mediator for sensory cues during locomotion. In addition, it could eventually lead to the conception of new walking aids for various populations.

Key words: postural control, haptic supplementation, aging, gerontechnologies

Résumé. Supplémentation haptique et contrôle postural chez les personnes âgées : Revue et perspectives pour les technologies d’assistance.

Cette revue met l’accent sur l’effet bénéfique d’une supplémentation informationnelle haptique, obtenue par un toucher léger sur une surface fixe ou mobile, sur le contrôle postural chez les personnes âgées. Dans une première partie, nous analysons les effets des altérations de l’intégration sensorielle liées à l’âge sur la stabilité posturale. Cette analyse s’effectue en relation avec les modèles actuels du maintien de la station érigée chez l’homme et des mécanismes sensori-moteurs du contrôle postural. Ensuite, nous présentons les dispositifs de biofeedback existants et les expérimentations les plus probantes sur la supplémentation haptique délivrée à l’aide d’un support tactile fixe ou mobile. En particulier, nous détaillons les résultats préliminaires d’un programme de recherche actuellement en cours dans notre groupe de recherche et portant spécifiquement sur l’efficacité d’un support mobile. Nous envisageons les applications potentielles de ces résultats. Finalement, nous suggérons que l’analyse des effets d’une « canne haptique » pourrait permettre de mieux comprendre comment les personnes âgées utilisent une aide à la marche de manière légère, comme un médiateur pour les entrées sensorielles durant la locomotion. De plus, ceci pourrait mener à la conception de nouvelles aides à la marche pour diverses populations.

Mots clés : contrôle postural, supplémentation haptique, vieillissement, gerontechnologies

1 Introduction: Age-related alterations of postural control and daily living activities

Aging is characterized by (more or less) progressive alterations of various structures and functions of the neuromusculoskeletal system (NMSS), which lead to a loss of behavioural adaptability and performance (Spirduso, Francis, & MacRae, 2005). Among the different functional alterations, those that affect postural and balance control are of particular importance since they determine the risk of falling, the degree of mobility and, finally, the autonomy of elderly people in daily living activities. For instance, around 30% of adults older than 65 years and 50% of those older than 80 years fall each year, with nursing home residents showing even higher percentages (Blake, Morgan, & Bendall, 1988; Tinetti, Speechley, &
Because of the demographical development of the population towards increasing life expectancy and the dramatic economic (public healthcare costs), physiological (hip fractures, death) and psychological (fear of falling, restriction of mobility, social isolation) consequences of falls, understanding the contributing factors to postural stability and balance control deserves closer attention by researchers in order to better prevent risk of falls and restriction of mobility in old age.

Classically, reinforcement of postural control mechanisms, as part of a (fall) prevention strategy, includes specific training programs (Lord, Sherrington, Menz, & Close, 2007, for review) and, in the most extreme cases, the prescription of walking aids to preserve postural stability (Bateni & Maki, 2005, for review; Stowe, Hopes, & Mulley, 2010). Actually, walking aids that are currently prescribed as a mechanical support prominently concern severely impaired older adults or fallers. However, one can speculate that most people suffering from infra-clinical alterations of postural control are at risk of falls and might benefit from “light” assistance in order to improve postural stability during walking in natural environments. On the basis of the existing literature on sensory supplementation and postural control, we suggest that supplementation of any of the contributing sensory systems could strengthen or assist balance control mechanisms and might be especially helpful to enhance mobility in elderly people or populations suffering from sensorimotor alterations of neural origin. As an illustration, sensory feedback devices such as electro-tactile vibration or galvanic vestibular stimulation are currently used as complementary tools during rehabilitation programs in people suffering from postural instability. Their underlying general principle consists of recording changes in body and head position and to feed back this information in real time to users by translating it into specific sensory modalities that are not altered or more sensitive than others (e.g. tongue) (Scinicariello, Eaton, Inglis, & Collins, 2001; Wall III, Wrisley, & Statler, 2009). Another strategy may consist of lowering sensory thresholds of mechanoreceptors by applying noisy vibrations (stochastic resonance) by foot insoles (Priplata, Niemi, Harry, et al., 2003) or on the level of the fingertip (Magalhães & Kohn 2011). Even though these strategies significantly enhance postural stability, the corresponding technological devices have however limitations with respect to their practical use in daily living (e.g., discomfort of electrotactile biofeedback of a tongue-placed device). Strikingly, in spite of a wealth of work on haptic supplementation in the context of postural stability (see seminal studies by Jeka & Lackner 1994, 1995), it is noticeable that the most classical and natural tool used to assist postural stability (i.e., a cane) has scarcely been considered as a possible medium for sensory (haptic) supplementation beside its function of mechanical support (see Boomsinsukh, Panichareon, & Phansuwan-Pujito, 2009 for a noticeable exception). The term “haptic” sense, introduced by Jeka and Lackner (1995) in the theoretical context of postural control, refers to the perceptual sense which combines cutaneous and kinaesthetic inputs from mechanoreceptors embedded in skin, muscles and joints of the arm and finger while touching or manipulating an object. It has been shown that haptic supplementation enhances postural stability of young and elderly people as well as patients with neuropathies or vestibular loss (Jeka & Lackner, 1994, 1995; Lackner et al., 1999; Dickstein, Shupert, & Horak, 2001; Baccini, et al., 2007). Moreover, contrarily to other existing sensory feedback devices, those providing haptic information might be easily integrated in existing walking aids and could constitute a mean to enhance postural stability in natural environments, especially during walking.

The present paper addresses the issue of haptic supplementation for improvement of postural control in the elderly. After presenting current models of human upright stance and sensorimotor mechanisms of postural control, we review the most influential studies on the effect of haptic supplementation on postural stability. Furthermore, we present preliminary results of a research program currently in progress in our group to investigate the effect of functional haptic information provided by a mobile support on postural stability and we speculate about potential applications of this available knowledge. We suggest that investigating the effects of a haptic stick prototype could help to better understand how elderly people use a walking aid in a “light” manner as a mediator for sensory cues during locomotion. In addition, it could eventually lead to the conception of new haptic walking aids for various populations.

2 Postural control

2.1 Postural stability and the continuous interactions between musculoskeletal, sensory and neural systems

It is currently admitted that postural control in human upright stance aims at the coordination of the multiple degrees of freedom (DoF) of the musculoskeletal system in order to achieve postural orientation and postural stability. Postural orientation refers to the ability to position the body’s segments relative to each other and to the environment. Postural stability refers to the ability to continuously keep the vertical projection of the body’s center of mass (COM) within the base of support (BOS) defined by the surface delimited by the feet. The high-positioned COM during upright stance corresponds to the point of application of constantly destabilizing gravitational forces that have to be counterbalanced by forces applied by the feet on the ground. Consequently, the COM position is currently considered as the variable to be controlled and the trajectory of the center of pressure (COP), which corresponds to the point of application of the ground reaction forces recorded by a force platform, is used as a common measure of postural stability (Prieto,
Myklebust, Hoffmann, Lovett & Myklebust, 1996; see below for details). Considering that even in an apparently quiet stance situation, the body continuously oscillates around its longitudinal axis, the term “static balance” sounds like a misleading denomination. Actually, to maintain balance, the deviation of the body from the vertical has to be sensed by means of central integration of orientation cues detected by the different sensory systems. Subsequently, corresponding adaptations of motor commands have to be addressed to the muscles of the different body joints in order to keep the COM above the base of support. Obviously, various environmental and task-inherent factors may consequently perturb postural control (Horak & Macpherson, 1996), in particular during highly constraining or suddenly changing situations (slippery surface, stairs, ...), thereby potentially leading to loss of stability and increasing fall risk. To maintain postural orientation and postural stability, the central nervous system (CNS) has to continuously manage the interaction between biomechanical, musculoskeletal, sensory, environmental and task-inherent constraints to keep the COM within specific boundaries of space, referred to as stability limits. Stability limits are determined by a coalition of factors, as for instance, the surface and form of the base of support, range of joint motion, muscular strength and sensory cues to detect these limits (Horak, 2006).

Due to multiple functional alterations in the NMSS, limits of stability considerably decline during aging (Horak, 2006; Blaszczyk, Lowe, & Hansen, 1994; Weiner, Duncan, Chandler, & Studenski, 1992). In the following, for simplification we will use only the term “postural stability” referring to both the ability to maintain upright stance due to the regulation of the COM and the ability to orient the body’s segments relative to each other and to the environment.

### 2.2 Measures of postural stability

A common measure of postural stability in both quiet stance and dynamic (perturbed) situations is the displacement of the COP recorded by a force platform underneath the feet of the participant (Prieto et al., 1996; Rougier, 2008). In these situations, COP trajectories result from corrective torque exerted by ankle and plantar flexion in the sagittal plane and by hip abduction and adduction in the frontal plane (Winter, Prince, Frank, Powell, & Zabjek, 1996). It is currently admitted that the COP oscillates continuously around the COM to maintain thus stable upright stance (Winter, McFadyen, & Dickey, 1991).

Time and frequency domains can be distinguished in the analysis of COP trajectories (Prieto et al., 1996). In the time domain, variables of interest usually represent the displacement and velocity of the COP, whereas in the frequency domain the variable of interest is the (shape of the) power spectral density of the COP. It is generally accepted that the larger (amplitude, range) and the more variable (root mean square (RMS)) the COP displacement, the less stable the participant and, accordingly, the less efficient the postural control system. Increased postural stability is currently considered as reflecting a better regulation of continuous COM deviations from its equilibrium position and manifests in smaller oscillations of the COP (Horak, 2000; Shumway-Cook & Woollacott, 2007). Thus, COM and COP measures appear quasi exchangeable in relatively stable quiet stance. Furthermore, elderly compared to young appear to perform oscillations with higher velocity (Demura, Kitabayashi, & Aoki, 2008; Du Pasquier et al., 2003) and frequency band power spectrum (Demura et al., 2008).

Quantification of the COP trajectories globally represents the amount of body sway and does not embody the structure of postural behaviour. In this respect, another method for analyzing the COP time series is the stabilogram diffusion analysis (SDA) proposed by Collins and De Luca (1993). A stabilogram diffusion plot corresponds to the mean square displacement of successive COP points as a function of increasing time intervals between points. SDA plots of normal quiet standing show a two-part control pattern, one for short and the other for long time intervals, which is interpreted as indicator of two time-related mechanisms simultaneously involved in postural control. On the one hand, for short time intervals, the postural system seems to be not controlled (open-loop) and consequently drifts away from its initial position. On the other hand, for long time intervals, corrective control takes place on the basis of feedback mechanisms (closed-loop). Collins, De Luca, Burrows and Lipsitz (1995) observed age-related changes in postural control mechanisms, showing that the transition between open-loop and closed-loop mechanisms takes place at longer time intervals and larger mean square displacement, which corresponds to increased instability compared to younger participants. Moreover, COP trajectories were more positively correlated over short-term and more negatively correlated over long-term periods. This corresponds to an increased drift-like behaviour and lower performance over short-term (stiffness with noise-like fluctuations) and a stronger control back to equilibrium over long-term periods of elderly people.

The structure of COP time series has also been suggested to represent specific aspects of postural control, which are not available in classical quantitative analyses (Pincus, 1991; Lipsitz & Goldberger, 1992). For instance, analysis of approximate entropy (ApEn) provides a measure of the regularity of COP fluctuations. A time series showing periodically repeated patterns of fluctuations has a relatively small ApEn, whereas a less predictable (i.e., more complex) pattern corresponds to a higher ApEn. By computing COP regularity by ApEn, COP time series showed more regular patterns in elderly people (Seigle, Ramdani, & Bernard, 2009) and pathological groups compared to young and healthy participants (Cavanaugh et al., 2006; Roerdink et al., 2006). Moreover, less regular patterns have been observed in balance...
experts than in control participants (Stins, Michielsen, Roerdink, & Beek, 2009) as well as during dual-tasking (Roerdink et al., 2006; Stins et al., 2009). Modifications of the structure of fluctuations of COP trajectories are interpreted in the context of complexity theories. They indirectly indicate the underlying changes in the coupling interactions of the different components involved in the postural control system, leading to loss of adaptability with aging (e.g., Lipsitz & Goldberger, 1992; Lipsitz, 2004). However, an increase in ApEn value for a given time series is not necessarily related to an increase in physiologic complexity (as for example in the case of white uncorrelated noise where ApEn tends to infinity. Consequently, to assess complexity of physiologic systems one should use diverse techniques that probe not only regularity but also nonlinear and fractal properties of the corresponding time series (Goldberger, Peng, & Lipsitz, 2002).

2.3 Models of human upright stance and postural strategies

Although the COM is an abstract notion (i.e., there are no afferent information that help sensing its location in space), stabilization of its position over time is often assumed as the implicit goal of postural control (e.g., Peterka, 2002). The control of the COM position indirectly results from mastering DoF (head motion, ankle and hip joint configuration). However, it still remains unclear which strategies are used by the CNS to achieve stable upright stance or balance, in particular during perturbation.

An appealing and commonly accepted assumption is that human bipedal upright stance can be modelled as an inherently unstable single-joint inverted pendulum rotating around the ankle that is with only one DoF. In this perspective, one considers that to maintain the alignment of body segments, the NMSS is primarily stabilized by active ankle control in combination with passive musculoskeletal structures. Thus, the inverted pendulum model relies on a presumably linear relationship between muscle activation and behavioural output variables (e.g. COM and COP trajectories or head position in space), and simplifies the problem of multisensory integration for postural control. Nevertheless, the single-joint inverted pendulum is currently considered as reference model in the literature and it has inspired most postural control studies (Maurer, Mergner, & Peterka, 2006, Peterka, 2002).

However, such a simplification of sensorimotor control falls short in most real, dynamic situations in which postural adjustments are necessarily made using several DoF of the multi-segmented body. Indeed, it has been shown that, as for most of our coordinated movements (Bernstein, 1967), successful balance of the unstable body during upright stance requires coordinated control of several body components (Hsu, Scholz, Schönner, Jeka, & Kiemel 2007; Kiemel, Elahi, & Jeka, 2008; Ting & McKay, 2007). However, controlling the covariation of joint angles does not seem to be the ultimate postural goal of the CNS. According to the logic of the uncontrolled manifold (UCM) framework, it has been hypothesized that the CNS aims to control specific variables (COM, head) through movements distributed over different joints. UCM is a method that divides the variance of joint configuration with respect to a given COM position in two components (Scholz & Schöner, 1999). The first subspace (or manifold) of joint postures is composed of all combinations of joint positions, which are equivalent with respect to the task-related variable being stabilized (COM position). Joint variance in this space can consequently be left “uncontrolled” without consequences for COM position or body sway variability. The second subspace, orthogonal to the first manifold, defines a space in which joint variance affects the outcome of the COM position. For instance, recent studies suggested that multiple DoF are used to control body sway even during quiet standing, thereby confirming that the single-joint pendulum model is an approximation that does not capture the different coordination patterns involved in postural control. Owing to the co-phase analysis of different body segments, Creath, Kiennel, Horak, Peterka, & Jeka (2005) showed that two modes of coupling between legs and trunk occurred simultaneously in unperturbed stance. Specifically, these two segments have been found to oscillate in-phase with respect to each other for low frequency ranges (i.e., < 1 Hz) and anti-phase for higher frequency ranges (i.e., > 1 Hz) (see also Zhang, Kiemel, & Jeka, 2007). Furthermore, Hsu et al. (2007) used the UCM hypothesis to study multi-joint coordination in postural control. The authors found that joints other than ankle and hip demonstrated noteworthy variance during quiet standing and that the CNS coordinated these redundant DoF to have limited effect on the task-related variable that means to minimize disturbance of the COM position. In summary, from a kinematic point of view, all DoF along the longitudinal axis of the body were engaged in postural control, whereas most of the variance was generated in the subspace in which the COM position was unaffected.

Multi-segmental coordination patterns were frequently observed to maintain upright stance in response to a large translation of the support surface. Indeed, in this dynamic situation, the so-called ankle strategy does not suffice to keep the COM above the BOS (i.e., to preserve postural stability). Instead, the so-called hip strategy, which manifests in the use of two DoF (ankle and hip), seems more appropriate. It corresponds to an anti-phase coordination pattern between the lower and the upper body segments (Bardy, Marin, Stoffregen, & Bootsma, 1999; Bardy, Oullier, Bootsma, & Stoffregen, 2002; Horak & Nashner, 1986; Horak & Mepcherson, 1996). Thus, the ankle strategy is usually observed in response to smaller perturbations. As suggested by Bernstein (1967), joint coordination patterns (muscle
synergies, Ting & McKay, 2007) reflect a neural strategy of functional coupling of groups of muscles acting together as a unit, thereby simplifying the control of multiple DoF by the CNS. In the context of postural control, postural strategies have been primarily interpreted as the result of voluntary selection of a central motor program permitting to manage postural constraints in order to maintain upright stance (Horak & Nashner, 1986; Nashner, 1977). However, different interpretations have been proposed on the basis of the dynamic properties of postural strategies observed when participants were instructed to sway in order to track a visual, back and forth oscillating stimulus. When the stimulus frequency increased throughout the trial, participants spontaneously switched from in-phase (ankle strategy) to anti-phase patterns (hip strategy). Moreover, the occurrence of the transition was modulated by biomechanical and task constraints. Drawing a parallel with the dynamic patterns observed in numerous multi-segmental action systems and conceptualized by Kelso and collaborators (Kelso, 1984; see Kelso, 1995 for an overview), Bardy et al. (1999, 2002) suggested that the postural strategies emerged as self-organizing patterns from a coalition of internal and external, task-specific constraints (support surface, visual tracking task). Accordingly, they challenged the hypothesis of centrally selected muscle synergies/postural strategies. In summary, since the body is a multi-joint system (Alexandrov, Frolov, Horak, Carlson-Kuhta, & Park, 2005; Hsu et al., 2007), postural control may exploit joint redundancy through the use of different flexible coordination patterns between ankle, knee and hip that are assembled as function of task and environmental constraints. This multi-joint model of the body provides a more realistic model of complex postural behaviour, as compared to the single-link inverted pendulum model.

However, modelling postural control as a single-link inverted pendulum simplifies likewise the investigation of underlying mechanisms of feedback control and more specifically of multisensory integration. Therefore, most authors advocated in this context that the simple model constitutes an acceptable approximation in a wide range of postural situations. Thus, in the following sections, we consider the single-link inverted pendulum model as a reference model for the study of multisensory integration and the effects of haptic supplementation on postural stability.

2.4 Sensory feedback mechanisms in postural control

Few general principles of sensory integration underlie the different models of postural control that have been proposed in the literature. In the context of the single-link inverted pendulum, it is currently admitted that body oscillations (angular deviations from a reference position) are detected by the CNS through the sensory systems and more specifically through the processing and integration of multiple sensory cues to generate a corrective torque, in order to compensate for postural disturbances. The question of how such a system is controlled remains however a matter of debate.

Although some authors concluded that corrective torque originating from feedback is insufficient for stabilizing the body (Fitzpatrick, Burke, & Gandevia, 1996), it is currently accepted that maintaining upright stance is controlled by sensory feedback mechanisms, which provide visual, proprioceptive and vestibular afferences to the CNS (Maurer & Peterka, 2005; Peterka, 2002; Fitzpatrick et al., 1996; Mahboobin, Loughlin, Atkeson, & Redfern, 2009; Maurer, Mergner, & Peterka, 2006). Consequently, multisensory integration is influenced by both the integrity of different sensory systems and the central processing of different sensory cues. However, even though it is generally accepted that redundancy exists across the multiple sensory systems, the underlying sensory integration processes are still unclear (Mahboobin et al., 2009; Jeka, Oie, & Kiemel, 2000).

A widely accepted hypothesis is that self-motion perception is based on the integration of different available sensory information derived from signals related to position, velocity or acceleration in order to determine the spatial orientation and motion of the body with respect to gravity and the environment (Fitzpatrick et al., 1996; Peterka, 2002; Maurer et al., 2006). Moreover, few authors have suggested that force-related sensory cues provided by mechanoreceptors in the skin (of the feet) should be included in models of postural control (Maurer, Mergner, Bolha, & Hlavacka, 2000, 2001; Maurer et al., 2006; Cnyrim, Mergner, & Maurer, 2009). The different sensory cues provide each a specific frame of reference for spatial orientation due to a flow of sensory cues. Specifically, visual inputs provide a reference for verticality and for self-motion by detection of optic flow. One usually considers that proprioceptive inputs mainly provide a reference for the support surface (texture and quality of the support surface). However, Maurer et al. (2001) argued that the CNS might extract and use COP motion information from receptors in deeper structures of the foot, in complement with mechanoreceptors in tendons and joints. Referring to its functional role of informing the CNS about the gravitational ground reaction forces and their spatial distribution when a body leans on a stable support, this force-related control system was called “somatosensory graviception” by the authors. Vestibular inputs provide a gravito-inertial reference based on sensors providing acceleration of the head during quiet stance (Shumway-Cook & Woollacott, 2007). As combining different sensory information may engage transformation to a common consistent reference frame, a current challenge of postural control research is to understand how the CNS combines the orientation cues of different modalities to estimate body position and motion (Jeka et al., 2000).

In this context, the quiet stance paradigm has been extensively used to manipulate and better understand sensorimotor processes underlying the maintenance of postural stability. Experimental manipulation of different
sensory inputs in a broad series of studies (for example sensory organization test (SOT), Equitest, NeuroCom; Horak, 1987; Shumway-Cook & Horak, 1986) has permitted to assess the contribution of each sensory channel and their integration in postural control. According to the model proposed by Collins and DeLuca (1993, 1995), the CNS is continuously provided by sensory cues, which may be used to control body orientation by closed-loop control mechanisms. These mechanisms only operate beyond a certain sensory threshold value that is, when postural deviations from equilibrium become significant. Below the sensory threshold, open-loop control mechanisms take place thereby leading to a drift of the body away from its equilibrium point. Thus, this model includes both open-loop and closed-loop mechanisms and accounts for feedback delays or inherent noise in the system and finally simplifies the sensory integration problem in situations where no severe instability of the body is apparent. However, Maurer and Peterka (2005), Peterka (2002) showed that a simple feedback mechanism combined with a time delay could generate realistic SDAs. The authors proposed a very simple control model implemented with realistic parameters (body mass, height of the body COM, height of the ankle axis). In this model, the input represents two torques exerted about an axis through both ankle joints: 1) a disturbing torque that generates body sway and 2) a corrective torque that corrects the destabilizing torque. The corrective torque is supposedly generated by a neural controller receiving sensory input with a given time delay. In this context, sensory thresholds are non-linear, which means that they affect low intensity sensory signals more than higher ones so that body sway is better counteracted as the intensities of sensory stimuli increase. The outputs of the model are angular deviations of the body and COP trajectories. Due to changes in time delay, noise level, stiffness and damping parameters in their model, the authors mimicked realistic physiological COP profiles in both time and frequency domains. Though the model is realistic, it is unclear whether it reflects the way the CNS works to control posture. In particular, since this model is based on the single-link inverted pendulum model, it remains to be determined how it may account for the coordination among joints (Hsu et al., 2007). An appealing solution to this problem has been proposed by Kiemel, Elahi and Jeka (2008). In their study, the authors approximated human upright stance as a two-joint inverted pendulum with a musculoskeletal actuator at each joint. Their model is inspired by the control theory perspective and consists of two components, such as the plant (musculoskeletal system) which is being controlled and the feedback component representing changes in neural activation derived from orientation cues of different sensory systems about the body motion. The basic reasoning is that ongoing corrections in non-ballistic actions such as postural sway result from two sources: 1) feedback-driven corrections, which arise from changes in neural activation requiring time delays and 2) intrinsic, very short-time corrections, resulting from visco-elastic properties of the muscles, which do not require changes in neural activation. The plant is supposed to receive a single input sent by the CNS to activate the muscles in a coordinated fashion. Such control solution, in which all muscles are consequently functions of the single control signal (the single-input/multiple outputs assumption), reduces the problem of multiple DoF. The feedback processes include the mapping from body segment angles to muscle activations being determined accordingly by properties of the distinct sensory systems and central sensory processing and integration.

Even though postural regulation in constant sensory environments has been mainly considered as a linear process (Fitzpatrick et al., 1996; Oie, Kiemel, & Jeka, 2001) several authors defended the point of view of non-linearities in sensory integration processes that appear when sensory stimuli changed (Jeka et al., 2000; van der Kooij, Jacobs, Koopman, & Grootenboer, 1999; Mergner & Rosemeyer, 1998; Peterka, 2002). In this respect, different models of multisensory integration exist that differ with respect to weighting mechanisms: from independent channels (Peterka, 2002) to optimal estimation procedure (van der Kooij, Jacobs, Koopman, & van der Helm, 2001). For instance, Ting (2007) proposed that the simple summation of the different channels cannot permit to control posture and that an internal model that captures their combination is functionally required. Internal estimates, that mean reconstructions of external stimuli, are supposed to be more easily manipulated for cognition, memory, movement planning (Maurer et al., 2006). In a different perspective, Peterka (2002), Peterka & Loughlin (2004) proposed a simple multisensory feedback model (“independent channel model”). Peterka’s model takes time delays into account, i.e. the time needed for sensory integration, neural processing and muscle activation before the corrective torque can be generated. In contrast to earlier hypothesis of constant sensory weights (Fitzpatrick, et al., 1996), Peterka concluded that dynamic stimulus-dependant changes occur in the sensory contribution to postural control in healthy adults under a variety of environmental conditions. In other words, even though experimental manipulation based on a perturbation or deterioration of one or more sensory cues (for example galvanic stimulation (Séverac Cauquil, Tardy Gervet, & Ouaknine, 1998), vibratory stimulation of the calf muscle (Gomez et al., 2009), eyes closure (Jeka & Lackner, 1994), SOT) generally results in an increase of postural oscillations, sensory reweighting can to a certain extent induce compensatory mechanisms and prevent from direct functional deficits.

Exploiting the concept of sensory reweighting, Jeka and colleagues (Jeka et al., 2000; Oie, et al., 2001, 2002; Allison, Kiemel, & Jeka, 2006) extensively used the “moving room” paradigm where visual and somatosensory “touch” cues were simultaneously manipulated (by small sinusoidal movements). In testing participants during this twofold sensory manipulation, Oie et al. (2001) showed that young participants used both intra-sensory
dependencies within modalities and inter-sensory dependencies to maintain postural stability (Jeka et al., 2000; Oie et al., 2001). The former leads to a decreased gain of a perturbed inaccurate modality and the latter stands for the shift away from inaccurate sensory cues towards more accurate modalities. Since multiple sources of information are involved in maintaining postural stability, it appears to be advantageous for the CNS to reweight sensory inputs based on their location and/or their modalities (Jeka, 1997).

Even though mechanisms of sensory reweighting need further investigation, promising findings about the instantaneous stabilizing effect of sensory supplementation (light touch, galvanic vibration and vibro-tactile supplementation) do lend credence to the hypothesis about dynamic nonlinear interactions within and between different sensory modalities for postural control of young and elderly. On the basis of feedback models by Peterka (2002) and Jeka and colleagues (Jeka et al., 2000; Oie et al., 2001, Allison et al., 2006), we will develop our statement about the stabilizing effect of haptic supplementation to compensate for age-related alterations of the sensory systems and/or of multisensory integration processes.

3 Age-related decline in sensory integration and its impact on postural stability

In addition to age-related changes in neuromuscular (muscle weakness) and orthopaedic constraints (Lord & Ward, 1994), sensory impairments occur during aging as a result of peripheral alterations of different sensory systems and of central sensory processing involved in the integration of sensory cues. Since mechanisms of sensory reweighting cannot fully compensate for distorted or missing information, these alterations lead to modifications of the sensorimotor processes and consequently to deficits in adaptability of the postural control system, which manifest in behavioral instability in everyday life of elderly people (Maki, Holliday, & Topper, 1994; Horak, 2006; Baccini et al., 2007). Here, we present the different sensory systems involved in postural control and their age-related alterations.

Vision provides the CNS continually with information about body position and motion with respect to verticality and objects in the environment. Accordingly, age-related functional declines in distant contrast sensitivity and depth perception have been found to be independent predictors of increased instability in the elderly (Lord & Menz, 2000). Vestibular function is important in the context of postural stability as the vestibular system continually provides the CNS with information about angular acceleration of the head (semi-circular canals) and linear acceleration and tilt of the head relative to gravity (olitholithic system). Moreover, different reflexes help maintaining stable posture, such as the vestibulo-ocular (visual fixation during head movement) and the vestibulospinal reflexes (trigger of muscle activity in neck, trunk and extremities). Age-related impairments of the vestibular system lead to impairments in gait and posture especially when performing turns, head movements while walking or rotation of the support surface as well as to perceptive (vertigo, spatial disorientation) and oculomotor deficits (nystagmus, strabismus). Accordingly, decline of vestibular function has been linked to postural instability and a higher risk of falls (Baloh, Enrietto, Jacobson, & Lin, 2001). Proprioceptive information includes sensory cues arising from muscles, tendons, joints as well as touch sensation at the point of contact with a support surface in the environment. Proprioception provides the CNS with information about joint position, muscle length and velocity of contraction, relative movements of body segments, and surface characteristics of the environment by touch sensation and force distribution in the skin. Age-related declines in joint position sense of the knee have been observed (Skinner, Barrack, & Cook, 1984), as well as decreased plantar tactile sensitivity (Perry, 2006), which have been associated with increased postural instability (Menz, Morris, & Lord, 2005). In addition, impaired vibration sense at the knee, knee position sense and impaired tactile sensitivity at the ankle have been found to be independent risk factors for falls in the elderly (Lord, McLean, & Stathers, 1992).

The occurrence of age-related peripheral sensory loss combined with impairments of central processing has been shown to result in a less precise postural control (Teasdale, Stehnach, Breunig, & Meeuwsen, 1991; Horak, 2006). Age-related sensorimotor alterations lead to larger postural sway (Baccini et al., 2007). Consequently, the ability to flexibly adapt motor commands by multisensory integration and to preserve balance in various environmental conditions is considered one of the most critical factors for postural control in elderly populations (e.g., Horak, Diener, & Nashner, 1989).

The capacity to reweight sensory inputs as a reaction to perturbed sensory information has also been found to decrease with aging (Teasdale et al., 1991). This means that central mechanisms such as selection, processing and integration of multiple sensory cues appear to work slower and/or less accurately. However, Allison et al. (2006)’s result suggested that, even in higher age, the plasticity of sensorimotor processes and especially of multisensory integration is preserved. The authors compared young, elderly and age-matched fall-prone participants in the above mentioned moving room paradigm. The used “gentle” sinusoidal sensory perturbation about a relatively long time period (120 s) contrasted with previous studies that used severely changing sensory conditions. During these severe perturbations elderly appeared to deploy deficient central integrative mechanisms (Horak et al. 1989, Teasdale et al., 1991) such as slow sensory processing rather than deficient sensory reweighting itself (Woollacott, Shumway-Cook, & Nashner, 1986).

In this situation of gentle sensory perturbation, results by Allison et al. (2006) suggested that even in fall-prone participants, sufficient peripheral sensation allowed
intra- and inter-sensory reweighting similar to young participants. The influence of age on the time scales of sensory reweighting remains however unclear.

Further evidence of the capacity of dynamic sensory integration and reweighting comes from studies showing the stabilizing effect of sensory supplementation (Holden, Ventura, & Lackner, 1994; Jeka & Lackner, 1994; Albertsen, Temprado, & Berton, 2010) or sensory substitution (Danilov, Tyler, Skinner, Hogle, & Bach-y-Rita, 2007; Barros, Bittar, & Danilov, 2010) in young and elderly people.

4 Sensory supplementation to increase postural stability in elderly people

4.1 Biofeedback to enhance postural control

Recent work has proven that biofeedback devices are efficient to supply the postural control system with additional information about body orientation and motion to substitute or supplement (impaired) visual, somatosensory and vestibular sensory cues (Vuillerme et al., 2008). Moreover, stochastic resonance has been found to lower sensory thresholds, which ameliorates sensory integration and, consequently, postural stability. In the following, we present the different supplementation and stochastic resonance devices.

The principle of electro-tactile biofeedback is to provide information about head orientation with respect to gravitational vertical (artificially sensed by an accelerometer in antero-posterior and medio-lateral directions) through electrical stimulation of the tongue, which is moving in real time in correspondence to head orientation (Danilov et al., 2007; Vuillerme et al., 2008). High resolution of supplementary sensory information is given because of the dense mechanoreceptive innervations on the tongue and its large somatosensory cortical representation (Vuillerme et al., 2008). By cautiously keeping the dorsum of the tongue in contact with an electrode array of the device, subjects can continuously perceive position and motion of a low intensity stimulus on the tongue. The tactile stimuli are perceived by users as a continuous “buzzing” sensation (electro-tactile waveform presented at 200 Hz). During a session of familiarisation, participants must learn to maintain the stimulus in the center of the array by postural corrective movements. After a few days of training, patients with balance dysfunctions showed enhanced postural control (Danilov et al., 2007). Benefits were still observed even when the device was withdrawn. In another study, young healthy participants used the vibrating device in order to compensate experimental withdrawing of vision and alterations of somatosensory information under the feet. Results showed that the destabilizing effect of deteriorated somatosensory cues was attenuated due to biofeedback. Such findings confirmed the capability of the CNS to integrate head orientation cues perceived by the tongue to stabilize posture (Vuillerme et al., 2008).

A similar feedback device providing information about body tilt through a vibrating belt has been shown to improve medio-lateral gait characteristics of vestibular deficient subjects as well as performance in a clinical functional gait test (Wall III et al., 2009). The belt was placed around the waist equipped with a six-degree of freedom motion sensor that provided linear acceleration and angular rate information. By means of this information, online feedback about the body tilt from the vertical was calculated and transmitted to the user via an array of tactile vibrators around the torso. The vibratory stimulus on the skin was continuously provided at 250 Hz. The 48 tactile vibrators were activated depending on direction and magnitude of body tilt. Participants should learn (training period of 20 min) to interpret this stimulation of receptors that are rarely used for postural control. The authors concluded that this tilt feedback belt could serve as intervention device for decreasing the risk of falls in the elderly and patients.

In addition, the stabilizing effect of galvanic vestibular stimulation (GVS) has been tested in a situation of mechanical perturbation applied in the medio-lateral direction in young participants (Scinicariello et al., 2001). During bipolar binaural GVS, an electrical current was applied over the mastoid bones through electrodes to the vestibular afferents. In parameter-estimation trials participants were tested for their response to galvanic and mechanical perturbation. By means of sway responses appropriate galvanic stimuli were calculated to counteract mechanical perturbation. GVS was shown to attenuate body sway.

Finally, vibrating insoles have been found to enhance balance control in both young and elderly (Priplata et al., 2003; Dhruv, Niemi, Harry, Lipsitz, & Collins, 2002; Gravelle et al., 2002). It is noticeable, that elderly people benefited more from this intervention than younger. In fact, the transmission of information through a sensory system can be enhanced by application of noise to the system. In corresponding studies, subsensory mechanical noise (white noise signals, low-pass filtered to 100 Hz) has been shown to enhance sensorimotor function by lowering sensory thresholds and enhanced thereby postural stability.

In the following section, we will present the experimental paradigm of light touch (LT) of a body part (classically the fingertip) on an external object. Differing from the above mentioned feedback devices, which are based on translating body or head position information into a specific sensory modality which brings along the need to learn their decoding, haptic supplementation provides sway-related information through a sensory modality which is indeed not one of the main sensory contributors to postural control but still commonly used in critical postural situations – touch sensation of the fingertips.
4.2 Haptic supplementation in the context of postural control

In their seminal works, Jeka and Lackner (1994, 1995) demonstrated the role of supplementary haptic information provided by a light touch of the index fingertip on a stable support surface in the control of upright posture. The light touch (LT) paradigm consisted in an active touch (< 1 N) of the index finger on a stationary surface (Fig. 1a). Specifically, results showed that haptic supplementation during quiet upright stance reduced the magnitude of COP displacements even though contact forces on the fingertip were too small to mechanically stabilize posture. Afterward, several studies have confirmed the benefit of haptic cues to decrease postural sway (Baccini et al., 2007; Dickstein, Shupert, & Horak, 2001; Krishnamoorthy, Slijper, & Latash, 2002; Rabin, DiZio, Ventura, & Lackner, 2008). Baccini et al. (2007) found that a LT was more efficient for elderly than for younger people with eyes closed. Moreover, concerning elderly patients with peripheral neuropathy (Dickstein et al., 2001) and with loss of vestibular function (Lackner et al., 1999) have been shown to benefit from haptic supplementation by light touch and enhanced postural performance.

Concerning theoretical interpretations of the benefits of haptic supplementation, Jeka and Lackner (1994, 1995) suggested that touch on a stable support surface provided a precise reference frame to the participants facilitating the detection of self-motion and body position in the environment and, finally, permitting adaptive corrections with respect to postural oscillations. Moreover, it has been shown that a LT generates both sway-related changes in contact forces on the fingertip and proprioceptive information regarding arm and finger position, allowing the CNS to anticipate activation of postural muscles and by this means to reduce body oscillations (Dickstein et al., 2001; Jeka & Lackner, 1994; Krishnamoorthy et al., 2002; Lackner, Rabin, & DiZio, 2001; Rabin et al., 2008).

The existence of such a feed-forward mechanism has been supported by several works, which showed a constant time lag of 250–300 ms between the fingertip force and postural corrections observed by means of COP displacements (Jeka & Lackner, 1994, 1995; Lackner et al., 2001). Rabin et al. (2008) showed moreover that, for being effective, haptic cues upcoming from transient fingertip contact forces should be completed by congruent arm proprioception as perturbation of haptic cues by vibration of the biceps muscle during the LT but not restriction of the arm movements lowered the stabilizing effect. The authors concluded that incongruent information arising from mechanoreceptors of the arm joints and muscles resulted in a biased representation of the body position and thereby in a higher postural instability.

Another paradigm of haptic supplementation has been examined in several studies with a comparable stabilizing effect on postural control. It included a passive scratch stimulus (PS) applied to the skin of various body parts during quiet stance. A piece of rough surface is kept in contact with the participants’ skin during the whole balancing trial, which provokes movements of the swaying body relative to the stationary scratch surface. It has been found that this kind of sway-related haptic information (shear forces) enhance postural stability in young and in the elderly. Participants with greater postural sway have been found to benefit more from the PS (Rogers, Wardman, Lord, & Fitzpatrick, 2001). Moreover, the PS has been proven to be most beneficial for postural stabilization the higher the stimulus was applied to the body as greater stimulus amplitudes arise on higher parts of the body. Both procedures – the “light touch” and the “passive stimulus” – gave rise to similar interpretations. Overall, the results observed for the LT and the PS supplementation procedure suggested that the CNS uses the transient changes of forces arising from the contact of a part of the body with a stationary support surface to detect body oscillations and to increase postural stability.

However, advancing research on the LT paradigm (completed by findings concerning PS) has shown that a fixed point in the environment accounts to a lesser extent for the beneficial effect of a light contact during postural tasks but rather the informational flow on the level of fingertip mechanoreceptors (in combination with additional arm and finger proprioception). Krishnamoorthy et al. (2002) observed a stabilizing effect of the LT of a mobile support (hand-held handle linked via a pulley system to a 3kg weight). The handle displacements and transient horizontal forces on the handle during quiet stance were sway-related and appeared to help decreasing body sway in the absence of a fixed reference point. However, for maximum stabilization it appeared to be important to link haptic cues provided by touch of a fixed support (fixed reference frame) with the sway-related transient contact forces (informational flow). The authors concluded that if the transient contact forces were large enough the presence of a fixed reference point may not be necessary to stabilize upright stance. In addition, Reginella, Redfern, & Furman (1999) found a destabilizing effect of the touch of a mobile LT support which was oscillating in a sway-referenced manner with the participants. The authors concluded consequently that even erroneous information provided by sway-referenced sensory cues was integrated by the CNS which perturbed posture. A stabilizing effect on posture has been observed by Rabin et al. (2008). By fixing the entire arm during LT the finger slipped relative to the stable surface (< 3 N) but postural stability was still enhanced. The authors suggested that functional sensory information was gained within a certain stable and limited spatial area, within which the COP displacement was kept. Finally, a LT of a non-rigid slightly deformable and moving support significantly increased postural stability even though it was less effective than LT on a rigid surface (Lackner et al., 2001). The LT support (circular extremity of vertically mounted flexible filaments) provided a spatial region in which haptic cues were available. Krishnamoorthy et al.
In view of further potential application in the domain of mobility aids, it should be however demonstrated that haptic supplementation is also effective when provided by a cane or a long stick that is, when the support surface is unstable. Indeed, although several authors emphasized the importance of a hand-held cane to provide haptic supplementation and functional spatial information, the question remains of whether and in which conditions the CNS can detect the relationship between the environmental surroundings and the oscillating body by the help of a mobile stick, presumably mediating the haptic sensory cues. This topic will be addressed to in the following paragraph. Recent results showing the stabilizing effect of haptic supplementation by a mobile touch support will be presented.

5 “Light touch use” of a mobile stick

The results observed in several studies might lead to expect that a LT on an unstable support could provide useful spatial information to control body sway (Boonsinsukh et al., 2009; Jeka, Easton, Bentzen, & Lackner, 1996; Jeka, 1997; Krishnamoorthy et al., 2002; Lackner et al., 2001). Jeka et al. (1996) were the first to investigate the possible benefit of a cane as a source of sensory information to improve postural stability. In their experiment, subjects stood in a Romberg tandem stance position and were instructed to lightly grip the handle of a cane (< 2 N). Two orientation conditions – vertical and slanted in medio-lateral direction (70° with respect to the horizontal) – of a mobile cane, pivoting around its fixed extremity, were assessed. Results showed that the slanted condition was more effective than the vertical one in reducing postural sway. To explain these results, the authors suggested that, contrarily to the vertical cane, the slanted stick did not move in the direction of the participant’s body oscillations. Subsequently, it led to functional sway-related contact forces as the result of the resistance offered by the inclined cane to medio-lateral oscillations. This conclusion is consistent with other results showing that stabilization resulting from LT was most effective when force changes were generated in the plane of greater instability (Rabin, Bortolami, DiZio, & Lackner, 1999).

However, the question of whether and how sensory cues can be functionally delivered during locomotion has been only scarcely studied. Only the study by Boonsinsukh et al. (2009) has investigated the role of a cane as a mediator of sensory information used in a “light grip” manner during locomotion of stroke patients. The authors found enhanced medio-lateral stability during locomotion in the patients during “light” cane use as well as higher muscle activity of the paretic leg compared to a “force” cane use which diminished paretic muscle activity. Yet, it is unknown if certain groups of participants (elderly, fallers) would benefit more than others of such kind of haptic supplementation in postural tasks. To answer this question, we explored in a first experiment the effects of different conditions of haptic supplementation provided by a lightly gripped (light grip, LG) fixed support or a mobile stick during quiet stance (Albertsen et al., 2010).

We applied this paradigm in a second experiment to two different groups of participants, young and elderly healthy participants. In the following we will give a side note to explain the methodological elements of the haptic supplementation experiments realized in our research group.

5.1 Light grip paradigm

In our experiments the participants stood on a force platform, eyes open, with both arms fixed along each side of their body by a belt. Their feet were placed at hip-width, side-by-side. Participants were asked to fix a point placed in eye heights on the wall and to stand as stable as possible. Six experimental conditions were run in a randomized order across participants: 1) a quiet stance condition was used as a reference condition (QS) and 2) a condition of stable support (LG) was carried out, in which participants were instructed to grip the stable stick support lightly (< 1.6 N) with three fingers (index, thumb and middle finger) of their right hand while the inclined stick was attached at its rear extremity on an adjustable metal structure (Fig. 1b).

The mobility of the stick and its resistance to body oscillations in AP direction were manipulated in four conditions of mobile support which will be presented in the
following: 3) an upright standing task in which participants held the stick lightly on the handle in a roughly horizontal equilibrium position without touching the ground (NTC), 4) a condition of light grip in which the stick handle was mobile while the end of the inclined stick was immobilized on the ground in AP direction (CB) and 5) a condition of light grip in which the inclined stick was free to move on either a slippery (CLL) or 6) a rough surface on the ground (CLR) (Fig. 2).

The handle of the stick was instrumented with three micro switches dedicated to the index finger on top of the stick handle and the two others dedicated to the thumb and the middle finger on both lateral sides. Each of those switches released and lightened a LED when the force exerted by the corresponding finger exceeded 1.6 N thereby ensuring that grasping forces did not give rise to a mechanical aid. The position and height of the stick were both adjustable while keeping a steady angle of 30° relative to the ground. The rationale for the choice of surface was that the slippery surface should provide shear forces on the stick extremity, which were of less magnitude informing about body sway than those provided by a rough surface.

Center of pressure (COP) trajectories were computed in the antero-posterior (AP) and medio-lateral (ML) directions. Based on COP trajectories, three dependent variables were calculated for each trial: 1) the root mean square (RMS), which represented the mean sway amplitude and was calculated for each trial after subtracting the average position of COP from each data point, 2) the range of amplitude of the COP displacement calculated by subtracting the greatest from the lowest value of the COP and 3) the mean COP velocity calculated by dividing the total length of the COP trajectory (approximation by summing the distances between two successive points with its coordinates x, y linked by a straight line) by the sampling time.

Seemingly furnishing sensory cues in both AP and ML direction, a LG of a fixed support was included in the experiment. One of the conditions of stick use (CB) represented touch of an inclined stick fixed on the ground but mobile on the hand-held handle. This condition presumably provided detectable sway related changes in contact forces on the fingertips in the AP direction but not in the ML direction. In other conditions, both the handle and the extremity of the stick support were mobile (NTC, CLL, CLR) e.g. in the NTC condition where the stick was hand-held without touching the ground. Presumably, this condition helped to test the influence of transient inertial forces created by the hand-held weight of the stick without any contact to the ground, i.e. in absence of haptic sway-related information by a resistance on the ground in any direction. In two other conditions, the stick extremity was scratching on either a rough (CLR) or a slippery (CLL) surface as the result of body oscillations in the AP direction. These conditions presumably provided more or less easily detectable changes in contact forces in the AP direction but no sway related haptic information in the ML direction. We hypothesized that changes in contact forces, which would result from the movement of the tip of a stick on a limited region on the ground, could provide a sufficient resistance to body sway to give rise to functional sensory supplementation and, finally, to postural stabilization (Lackner et al., 2001).

In summary, our study differed from previous LT studies of the literature with respect to at least four important aspects: 1) the natural quiet stance situation in which the participants were tested; 2) the LG with three fingers permitting to hold the stick; 3) the fact that the handle and the extremity of the stick support were either stable or mobile in both AP and ML directions and 4) the fact that in some conditions, the extremity of the stick scratched on a slippery or a rough support surface.

5.2 Aims and results of light grip experiments

Thanks to different experimental conditions, we investigated how haptic supplementation obtained through a three-digit light grip (LG) of a fixed or mobile stick support influenced postural stability. Our main hypothesis was that postural stabilization should be even observed in mobile stick conditions that is, independent of the nature of the support. We predicted that it should be the case when contact forces resulting from a resistance in opposite direction to body oscillations provide detectable feedback information to the participants related to their body motion.

Results showed that among the stabilizing conditions in AP direction, one was provided by a fixed support (LG) and the two others by a mobile support (CB, CLR). These findings suggested that the three conditions of haptic supplementation shared, at least in part, common
characteristics with respect to sensory inputs provided to the participants for the control of body oscillations. This interpretation was in agreement with Krishnamoorthy et al.’s (2002) results suggesting that the availability of a fixed support for the LT may not be necessary to reduce sway, under the condition that the modulations of contact forces during a LT are large enough. Since in the mobile support conditions the CNS could not use a stable reference point to control body oscillations, it can be put forward that the three conditions (i.e. including those with mobile support) provided haptic cues by changing contact forces and proprioception related to body oscillations. Since the mobile conditions (CB, CLR) produced a comparable stabilizing effect to the one produced by a fixed support, one can hypothesize that the resistance in opposite direction to body sway played a prominent role in the control of postural stability by creating sway-related transient contact forces. We hypothesized that changes in contact forces, which would result from the movement of the tip of a stick on a limited spatial region on the ground (CLR), could provide postural stabilization (Lackner et al., 2001).

The absence of postural stabilization observed in the CLL condition was more surprising. Indeed, since the stick moved on the ground on a slippery surface, we expected to observe a (even though smaller) stabilizing effect despite the reduction of sensory information as compared to a rough surface (CLR condition). This expectation corresponded to Jeka and Lackner’s (1995) findings about the equivalent stabilizing effect on posture of fingertips LT on a support surface with different frictional properties (i.e. slippery and rough). In contrary to the present experiment, no relative movement between finger and support were observed. Furthermore consistent in sense are results observed by Lackner et al. (2001), which revealed a smaller but significant stabilizing effect of flexible filaments that provided a smaller spatial stability and less resistance to touch compared to rigid filaments. However, to explain the missing stabilizing effect of the CLL condition in the experiment, one could suggest, that body oscillations were too small to make the information resulting from the movement of the stick on the slippery surface detectable and usable for postural control. Our findings suggest that a stabilizing effect on posture can be gained, even in absence of a stable spatial referent, under the condition that sufficient functional transient contact forces are provided, which is conforming to the hierarchical effect of fixed and mobile supports proposed by Krishnamoorthy et al. (2002).

The above mentioned results in AP were obtained for young and for healthy elderly participants tested in the same paradigm. A group effect (range of COP, mean velocity) indicated that at baseline the healthy old participants were more instable than younger. Contrary to the expectation that elderly (more instable participants) could enhance postural stability more than young (more stable participants) with the help of additional orientation cues, all participants appeared to benefit to the same extent of haptic supplementation.

Comparing mobile and fixed LG supports, did not allow however to rule out the possibility that a fixed support provides a reference frame to the participant which facilitates “reading” of body motion. Since stabilization of postural sway disappeared for the slippery surface condition (CLL), as compared to the rough surface, one could conclude that the flow of information provided at the fingertips during touch of a mobile support on a rough surface supplies effectively with haptic cues that enable to better control ones balance. The observed postural stabilization resulting from lightly touching the support could either occur: 1) due to an enriched sensory environment during light touch, which helped therefore to perceive self-motion perception (supplementation), or 2) due to dynamic sensory reweighting processes in the integration of orientation cues which would mean that deficient orientation cues are replaced by other cues from intact sensory modalities (substitution). Future studies testing different groups of population should aim to distinguish between the two above mentioned aspects of multisensory integration.

These results constitute an encouraging step towards the investigation of the stabilizing effect of haptic supplementation by the help of a mobile stick. Indeed, haptic supplementation appears to have a potential to be easily incorporated in a low-cost walking device, which immediately could enhance postural stability. Beside its classically known biomechanical benefit, a mobility aid could potentially incorporate spatial orientation information upcoming from sway-related haptic feedback via light grip. Both, the mechanical support function and the supplementation of orientation cues, could at last help to enhance postural stability in the elderly. Thus, a continuation of the present experiment will consist in applying this “mobile stick paradigm” to complex situations while targeting different groups of participants. It would be beneficial to approach everyday life situations in which an informational stick could potentially be of assistance to gain stability and mobility. Experiments are currently in process to address these issues. In the following section we speculate on the advantages that could be offered by haptic supplementation as compared to existing sensory feedback devices.

6 Potential applications of haptic supplementation in the domain of mobility aids

A common prevention strategy to improve balance and mobility in elderly people lies in the prescription of walking devices such as canes or walkers. Even if it has been suggested that canes may help postural control by providing mechanical support as well as somatosensory feedback (Bateni & Maki, 2005; Boonsinsukh et al., 2009), they
are primarily prescribed to provide mechanical stabilization. Indeed, mechanical support provided by the cane is known to help controlling the motion of the COM and to prevent instabilities or recover balance after a perturbation by enlarging the base of support, bearing weight and/or generating reaction forces in order to limit large COM displacements (see Bateni & Maki, 2005 for review). Consequently, mobility devices are also supposed to increase user’s feeling of safety and confidence (Tinetti & Powell, 1993). However, it has been shown that the use of walking devices may also have deleterious side effects (Tinetti & Powell, 1993). Indeed, because they require intensive training for familiarization, canes may (initially) impair mobility of older people and be a cause of accidents, for instance by distracting attention from gait. On the basis of their results, Maki et al. (1994) even claimed that cane use predisposed elderly to increased risk of falling.

In contrast to the well-known mechanical function of canes, benefits of somatosensory information have been scarcely explored and, they are thus not actually considered as promising for technological developments of assistive mobility devices. Nevertheless, in everyday life situation, lightly touching a handrail while descending stairs, slightly scratching a wall in rooms of complete darkness or even just touching the forearm of a partner during locomotion (as frequently observed in elderly instable people), seems to manifest the need of touch orientation cues that enrich the sensory environment during locomotion and presumably help to control COM motion. However, although the observed stabilizing effect of haptic cues provided by a fixed (Jeka & Lackner, 1994, 1995) or a mobile support (Albertsen et al., 2010) is of potential relevance to mobility aids, few works have systematically explored the benefit of haptic cues provided by a cane on postural stability during locomotion. In a recent study, Boonsinsukh et al. (2009) investigated the effect of the use of somatosensory cues provided by a light cane use in stroke patients. During light cane use conditions, the patients obtained spontaneously an intermitting cane use which was interpreted as a need of additional sensory cues in form of regular “boosts” (rather than continuous cane contact). Moreover, patients were found to lightly use the cane during the single-limb stance on the paretic leg which is the most difficult moment during walking of a stroke patient. Results showed that the participants not only increased medio-lateral stability but also enhanced muscular activation in the affected leg. In contrast, in a study by Buurke, Hermens, Erren-Wolters, & Nene (2005) with stroke patients, it has been shown that a conventional cane use (force contact) with the body weight being shifted towards the cane (ipsilateral to affected leg) the paretic leg showed decreased activation during walking. Thus on the basis of Boonsinsukh et al.’s findings (2009) one may be confident with respect to the conception of informational canes, which could be used in the rehabilitation of normal gait patterns or in everyday life of instable people. One could suggest that a light cane use might help individuals to explore the relation between self-motion and environment (i.e., the ground) due to light touch orientation cues. This enriched sensory environment might help to increase stability and resistance to perturbation in difficult postural tasks. These hypotheses should be however tested in elderly people. In particular, the question remains of whether haptic information may help mastering DoF in the multi-joint coordination system involved in postural tasks and locomotion (see for example Zhang et al., 2007). Indeed, until now, the single-link inverted pendulum model has been widely considered satisfying to test hypotheses about the stabilizing effect of sensory supplementation provided by a light touch on a fixed support. Investigating the role of haptic supplementation in multi-joint coordination would permit to approach real life situation in which instable people might benefit from sensory supplementation provided by assistive mobility devices. In addition, if one hypothesizes that force cues permit controlling COM excursions during locomotion, it should be verified in future experiments. In particular, the optimal level of force cues that has to be generated in the hand to improve COM control during gait should be determined.

Implemented in informational canes, haptic supplementation would have some advantages over the existing feedback devices as, for instance, those consisting in a tongue-placed electro-tactile biofeedback device. Indeed, it has been shown that the body or head tilt feedback could only be used after a period of practice. Contrary to sensory supplementation of the artificially sensed body or head tilt information, changes in haptic cues in the hand might directly provide sway-related orientation information. According to the results observed in most studies on haptic supplementation in postural tasks, available orientation cues appear to be automatically incorporated by the CNS in the process of multisensory integration as a part of postural control. Thus, even though haptic cues are provided via a sensory modality (tactile sensation in the hand) that is unusual in postural control, exploiting haptic information provided by a cane would probably not require extensive learning (see Danilov et al., 2007). It remains however to extend the results observed in static postural tasks to more complex, dynamic situations, including locomotion. Indeed, it could be that during locomotion, when multiple DoF have to be controlled, the CNS could encounter more difficulty to use haptic information. In particular for elderly, the light cane use could be attention-demanding. However, Lövås et al. (2005) showed a diminished attentional cost during spatial navigation on a treadmill due to touch of a handrail. Thus, by means of greater feeling of safety, enriched sensory environment and/or facilitation of self-motion perception, attentional costs could decrease after a short period of familiarisation, which would improve postural stability and mobility and therewith decrease the risk of falls. Nevertheless, the question remains of how haptic information can be provided in order to be fed back to individuals during gait. In this respect, the handle could potentially
be equipped with vibrators which lower sensory thresholds via stochastic resonance to enhance informational flow (see Magalhães & Kohn, 2011 for an illustration). Another question is whether such devices should include the classical function of weight bearing and enlargement of the base of support.

7 Conclusion and perspectives

In view of the prevention of falls, extending experiments about haptic supplementation to dynamic situations will help to identify if the LT phenomenon is transferable to real life with a potential to enhance stability and mobility in the elderly. The conception of an informational cane prototype providing haptic supplementation and the exploration of its use by elderly people (of different populations) in normal life are future challenge of our research group and, more generally, for gerontechnologies. Moreover, studies with vestibular patients or lightly affected hemiplegies patients, for example, could help to understand more precisely the influence of haptic supplementation on multisensory integration mechanisms of impaired postural control systems. Hypothetically, this research could lead to mobility devices of a new type (informational, biomechanical or both), more adapted to needs and deficits of less impaired people than those needing a firm biomechanical support. Of course, attentional, neuromuscular, metabolic, physiological (fatigue) and psychological consequences of these devices should be determined before being proposed to a large audience.

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