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Inke Marie ALBERTSEN

EFFECTS OF HAPTIC SUPPLEMENTATION ON POSTURAL STABILITY IN STANDING, PERTURBED STANDING AND SITTING IN OLDER ADULTS

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Jury

BARDY, Benoît (Examiner)	Université de Montpellier 1
HEUER, Herbert (Reviewer, Co-supervisor)	Technische Universität Dortmund
NOUGIER, Vincent (Reviewer)	Université Joseph Fourier
PAPAXANTHIS, Charalambos (Examiner)	Université de Bourgogne
SPIJKERS, Will (Reviewer)	RWTH Aachen
TEMPRADO, Jean-Jacques (Co-supervisor)	Aix-Marseille Université

Abstract

The present work was dedicated to the study of haptic supplementation, an experimental manipulation that allows augmenting the sensory cues available to the CNS. It has been found to provide a stabilizing effect on the postural stability of young and older participants. Besides the classically employed experimental manipulations, namely sensory restriction or perturbation, haptic supplementation proved to be a complementary way of studying how postural control is achieved in changing sensory environments. Two paradigms of haptic supplementation during upright stance have been studied in the literature 1) the light-touch paradigm consisting in a light contact of the index finger on a fixed support and 2) the passive-stimulus paradigm consisting in a light passive "scratch" of a stationary rough surface to the skin. However, it remained unclear whether haptic cues provided by a fixed or mobile support improved postural control in a similar way and whether the stabilizing effect of touch cues persisted in perturbing postural tasks. Finding answers to these remaining questions is of crucial importance in view of potential applications in the domain of (informational) walking devices. This was the objective of the present work, which aimed to contribute to the better understanding of the underlying mechanisms of the potential stabilizing effect of haptic cues from a mobile support. A prerequisite of the present work consisted in the design and use of a mobile-stick experimental paradigm that is, a combination of a light touch (via a mobile support) and a passive stimulus (sway-related movements of the mobile support). Owing to this paradigm, we aimed to explore whether and how the CNS can make use of haptic cues provided by the light contact of a mobile support. In <u>the first part</u> of the current manuscript, we present a review of the literature about postural control and haptic supplementation. <u>The second part</u> describes the new mobile-stick experimental paradigm. <u>The third part</u> details the different experiments carried out to investigate if especially older adults can make use of additional haptic cues in different challenging postural tasks. Different variables calculated on the basis of the center of pressure (COP) were used to study changes in postural stability with or without supplementation. <u>The first experiment</u> examined the effect of haptic supplementation provided by a more or less stable support on postural stability of young participants during quiet stance. <u>The second experiment</u> furthermore compared young and older adults in the above-mentioned task. The results confirmed our hypothesis about the effect of haptic supplementation in both age groups, independent of the mobility of the support. In absence of a fixed reference point in the environment, that is, when haptic cues

from a mobile support were provided, participants still benefited from haptic cues presumably created by the sway-related movements of the support. When testing different levels of light resistance offered by the support against body sway, the results suggested that only sufficient resistance (scratch on rough surface) guarantees the stabilizing effect. The results further suggested that haptic supplementation reduces (over short time intervals) the reliance on increased activity of the involved muscles and leads (after longer time delays) to well-coordinated postural corrections. Even age-related changes in the stochastic behavior of the COP are compensated due to haptic supplementation, which is even more noticeable as clinical tests of cutaneous sensitivity showed an age-related decline of spatial acuity at the fingertip. In the third experiment, we were interested in the potential effect of haptic supplementation on postural control of sitting. Based on the assumption of common principles of feedback control during standing and sitting, we hypothesized that the CNS can also improve sitting postural stability when supplemented. The results confirmed this hypothesis for both age groups. We also manipulated visual cues in this study. Corresponding results suggested that additional haptic cues can substitute missing sensory information. This finding is valuable as haptic cues are not commonly used for postural control. In the fourth experiment, we aimed to explore whether haptic information from a mobile support is used by the CNS to control standing posture in a dynamic postural task. Together with the COP, in this study we also analyzed the coordinative pattern between the leg and trunk segments by means of kinematic data of young participants standing on a rocker board. Results suggested that the COP and the angular displacements of the two segments are reduced when haptic cues are available even though haptic supplementation does not influence the coordinative pattern (ankle strategy) established to achieve the rocker-board stance. The fifth experiment investigated whether haptic supplementation has a potential to improve the system's robustness to sudden support-surface translations. Younger participants reduced the time to the first correction of the COP when supplemented, whereas older adults did not behave in the same way. Owing to another age-related strategy, most likely, involving a more rigid body, the older adults corrected their posture earlier than young adults even without haptic supplementation and therefore did not make use of additional haptic cues to further shorten their postural correction in response to the external perturbation. Overall, experimental findings confirmed our hypotheses and therefore promote future research on the application of the mobile-stick experimental paradigm to locomotion. To conclude our work, the general discussion and the opened perspectives toward a portable haptic assistive device are presented in the last part of the present manuscript.

Acknowledgements

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List of abbreviations

AP	Antero-posterior
Area	Area covering the planar center of pressure displacements
BOS	Base of support
CNS	Central nervous system
COM	Center of mass
COP	Center of pressure
CorrLT	Cross-correlation coefficient
CorrLT_{pos}	Cross-correlation coefficient of the positively-correlated trials
CPmm²	Critical mean squared displacement
CPs	Critical time interval
Dl	Long-term diffusion coefficient
DoF	Degree of freedom
DoFs	Degrees of freedom
Ds	Short-term diffusion coefficient
EC	Eyes closed
EO	Eyes open
lag	Time lag
lag_{pos}	Time lag of the positively-correlated trials
LG	Light grip
LGb	Light grip blocked
LGf	Light grip fixed
LGh	Light grip horizontal
LGr	Light grip rough
LGs	Light grip slippery
LT	Light touch
ML	Medio-lateral
MPF	Mean power frequency
MTP	Mean total power
MV	Mean velocity of the center of pressure trajectory
N	Newton
NMSS	Neuro-musculoskeletal system
PA	Peak amplitude
PS	Passive stimulus
$\%_{pos}$	Percentages of the positively-correlated trials
QS	Quiet sitting (study III)
QS	Quiet stance (studies I, II, IV and V)
Range	Range of the center of pressure positions
RMS	Variability of the center of pressure positions
SDA	Stabilogram diffusion analysis
SIT	Rocker-board sitting
STANCE	Rocker-board stance
TC	Time to first correction
TRANS	Translation condition on sliding platform
w. Range	Weighted range

General introduction

Efficient postural control is important to preserve the autonomy of older adults during activities of daily living since it permits to accomplish supra-postural and locomotor tasks and to avoid falls. Age-related alterations of postural control can have dramatic consequences concerning the quality of life and the well-being of older adults. Thus, understanding how to improve postural control is an important objective of researchers in the domain of gerontology. This was the general objective of the present thesis.

A widely accepted hypothesis is that to achieve efficient postural control, the central nervous system (CNS) processes a variety of signals provided by the different sensory systems that inform about the spatial orientation and motion of the body with respect to gravity and the environment. Sensory integration allows to generate corrective motor commands addressed to the corresponding muscles and to accomplish postural corrections [Fitzpatrick et al., 1996, Peterka, 2002, Maurer et al., 2006].

For several decades, the prominent experimental strategy to assess the contribution of each sensory modality to postural control and to study multisensory integration has been the restriction or perturbation of different sensory inputs (e.g., sensory organization test [Horak, 1987]). Even though sensory restriction (eyes closure [Jeka and Lackner, 1994]) or sensory perturbation (galvanic stimulation [Séverac Cauquil et al., 1998]) generally results in an increase of postural oscillations, the CNS can compensate to a certain extent for these kinds of perturbations. This means that the CNS can decrease the weight of, for example, missing or inaccurate information from one sensory channel and simultaneously increase the weight of another (more accurate) one [Jeka et al., 2000, Peterka, 2002, Oie et al., 2001]. These compensatory mechanisms demonstrate the ability of the CNS to maintain postural stability in a constantly changing environment. However, compromised by age-, injury- or disease-related alterations of the neuro-musculoskeletal system (NMSS), the CNS can experience difficulties in sensing deviations of the body from gravity. If no more compensation can be accomplished, for instance, because of limitations in central processing or multiple alterations of the sensory systems, postural instability may result. Thus, from a methodological point of view, another complementary way to study postural control mechanisms is to supplement the system with additional sensory cues. During sensory supplementation the studied system is not additionally challenged or modified (as it is during sensory restriction), which could be an advantage especially when studying postural control systems that are already altered due to higher age. Thus, sensory supplementation, which has been proven to stabilize posture of young and older adults [Jeka and Lackner, 1994, Jeka and Lackner, 1995, Baccini et al., 2007] by augmenting sensory cues available to the CNS, could help to compensate for age-, injury- or disease-related alterations of the NMSS.

Consistent with these considerations, the present work is dedicated to the study of haptic supplementation, a way of providing the CNS with additional cutaneous and proprioceptive cues via a light touch (LT) between a body part and the environment during a postural task. It is largely inspired by the seminal works of Jeka and Lackner [Jeka and Lackner, 1994, Jeka and Lackner, 1995, Jeka et al., 1996, Jeka, 1997] that demonstrated the functional role of supplementary haptic information provided by a LT of the index fingertip on a stable support in postural control. The two main advances of the works by Jeka and colleagues were that haptic information from the fingertip helps to build an accurate representation of the body orientation due to the fixed reference point provided in the environment, improving postural stability. Although these authors often claimed potential applications of their findings in the domain of assistive devices, they did not fully exploit the possible benefit of a LT on a mobile support. This would be important however. Indeed, if observed, results about the stabilizing effect of a LT on a mobile support would challenge the above-mentioned interpretation associated to a fixed reference point in the environment. Few studies have investigated the effect of a LT on mobile supports (LT of a weight held by a pulley system or flexible filaments) and observed a stabilizing effect [Lackner et al., 2001, Krishnamoorthy et al., 2002]. Corresponding results suggested that increased postural stability might be gained through the use of another type of haptic information related to transient finger and arm proprioception as well as contact forces developed between the fingertip and the lightly-touched mobile support [Lackner et al., 2001, Krishnamoorthy et al., 2002]. Thus, sway-related haptic cues seem to improve self-motion perception and thereby postural stability, even in absence of a fixed reference point (e.g., [Krishnamoorthy et al., 2002]). Yet, the present work was motivated by the lack of studies exploring whether haptic supplementation is also effective when the support is mobile, oscillating with the swaying body. The lack of studies in this field convinced us to address this issue, which is especially important in light of potential applications in the domain of mobility aids toward a portable haptic assistive device.

Though several researchers and clinicians have emphasized the importance of a hand-held cane to provide haptic supplementation and thereby functional orientation cues [Bateni and Maki, 2005, Jeka, 1997], the question remained of whether and in which conditions the CNS can detect the relationship between the environmental surroundings and the oscillating body with the help of a mobile haptic support.

In addition to these theoretical considerations, the present work was also inspired by everyday-life observations. First of all, a number of cane-users actually do not use their cane as a mechanical support, given that their stability is not challenged. Instead, they use the cane intermittently in the gait cycle in order to make a light contact with the ground. One can interpret this strategy as a means of using the cane as a haptic support, which then provides sway-related orientation cues via the light contact of the cane with the ground. Second, one can think of situations, in which a person is entering the dark basement of a house while lightly touching the wall with the fingertips in order to find the light swift. The light contact of the fingertips with the wall, in this case, presumably provides sway-related orientation cues to preserve balance during locomotion. Finally, one can often observe older adults lightly touching the forearm of a nurse or a family member with the hand while walking. Might this, similarly, reflect a situation, in which older unstable adults gain sway-related orientation cues via the light contact of the fingertips with the moving arm of the partner? From these observations, we hypothesized that sway-related haptic information is provided in all three mentioned complex postural tasks, that it enhances sensory cues available to the CNS and thereby improves postural control. In all the mentioned situations, the user of haptic cues moves in the environment which, thus, justifies the need for research on mobile haptic supports and for the design of a portable haptic assistive device. These examples illustrate what we think is the added-value of haptic supports that are currently used in daily life, such as a lightly-used cane or a lightly-touched arm of a partner during locomotion. The potential mechanical function and the psychological benefit that this kind of support could also provide will not be outlined in the present work.

Based on the literature about the LT and on the above-mentioned everyday-life observations, the motivation for the present work was fourfold. First of all, we aimed to better understand multisensory integration processes of visual, proprioceptive, vestibular and haptic cues and how haptic cues provided by a mobile support influence postural control mechanisms.

Moreover, we intended to determine if these cues can compensate for missing yet commonly used sensory sources (visual, proprioceptive and vestibular). Second, we aimed to investigate how haptic supplementation from a mobile support influences postural control of older adults and if they benefit more or differently from haptic cues than young adults, for example, due to peripheral or central infra-clinical alterations of the NMSS. Our third objective was to explore the effect of haptic cues provided by a mobile support on sitting posture. Indeed, even though similar models exist for standing [Kiemel et al., 2008] and sitting postural control [Reeves et al., 2007], few works have tried to compare postural control mechanisms in both tasks (see [Genthon and Rougier, 2006, Preuss and Fung, 2008, Vette et al., 2010], for exceptions). Moreover, a lot of work in the domain of sitting postural control focused on deficient postural control of patients with low back pain [Radebold et al., 2001, Van Daele et al., 2009, van Dieën et al., 2010] or stroke [Genthon et al., 2007, Perlmutter et al., 2010] but rarely studied the postural control system during normal aging. By exploring, in a first step, the effect of haptic supplementation on postural control of sitting in healthy older adults, we intended to clear the way for future research about the potential compensatory effect of haptic supplementation on sitting posture in sensory- or motor-deficient populations. Finally, our fourth objective was to investigate the missing link between the actual theoretical knowledge about haptic supplementation (via fixed or, at least, not portable supports) and potential applications in the domain of assistive mobility devices providing haptic supplementation. By studying the effect of haptic cues provided by a mobile stick in dynamic situations we aimed to determine whether these cues are beneficial for postural stability in perturbed situations. Besides their perspectives toward applications, corresponding experiments were also designed to better understand how the integration of haptic cues provided by a mobile support occurs when not only a fixed reference point is absent (mobile light-touch support) but also the user of the haptic support moves in space.

In the first part of the manuscript, we present a review of the existing literature on postural control, sensory integration, haptic supplementation, age-related alterations within the NMSS and their consequences for postural control (chapter 1.). The second part of the manuscript is dedicated to the experimental strategy of the present work describing experimental conditions that were, conceptually speaking, similar in the different experiments (chapter 2.). In the third part, we present the different studies that were inspired by the motivations presented above, their main results and discussions (chapters 3. to 7.). Lastly, we conclude by presenting the general discussion and the perspectives offered by the findings of the present work (chapters 8. and 9.).

1. State of the art

1.1. General principles of human postural control

1.1.1. Interplay of biomechanical and sensorimotor factors for postural control

Postural control results from the coordination of the multiple degrees of freedom (DoFs) 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), which is defined by the surface delimited by the feet (during upright standing) or by the buttocks and thighs (during sitting). In the present work, we will refer to postural stability defined as the ability to maintain posture due to the regulation of both the COM and the body segments relative to each other and relative to the environment.

The stabilization of the COM positions over time is often assumed as the implicit goal of postural control (e.g., [Horak, 2006, Peterka, 2002]): the COM is the point of application of constantly destabilizing gravitational forces that have to be counterbalanced by forces applied on the ground. So, mechanically, standing is a more challenging task than sitting because the COM has a higher position relative to the BOS in the former than in the latter task. To maintain balance, the inherently unstable system has to be controlled. In this aim, the CNS detects deviations of the body from vertical by means of central integration of orientation cues from different sensory systems. Subsequently, feedback-based adaptations of motor commands have to be addressed to the muscles of different body joints. Coordinated muscle activations result in corrective forces applied to the ground, which keep the projection of the COM within the BOS. It is noticeable, however, that even in an apparently quiet balance situation the body continuously oscillates around its longitudinal axis in both the antero-posterior (AP) and medio-lateral (ML) directions. Body oscillations can be inferred from the trajectory of the center of pressure (COP) that is, the point of application of the resultant ground reaction force over time recorded by a force platform. Spatio-temporal features of the COP trajectory are, thus, common measures of postural stability ([Prieto et al., 1996], chapter 1.1.2.).

According to Newell (1986), motor skills "emerge" from the interplay of environmental, task-inherent and subject-related (biomechanical, musculoskeletal, sensory and cognitive) factors. Separate or concurrent changes in these factors may perturb postural stability [Horak and Macpherson, 1996] and the CNS has to continuously manage the interaction between these constraints (Figure 1). Any change in one of the different constraints may lead to a loss of stability and increases the risk of falling if the CNS is unable to compensate for the perturbation.

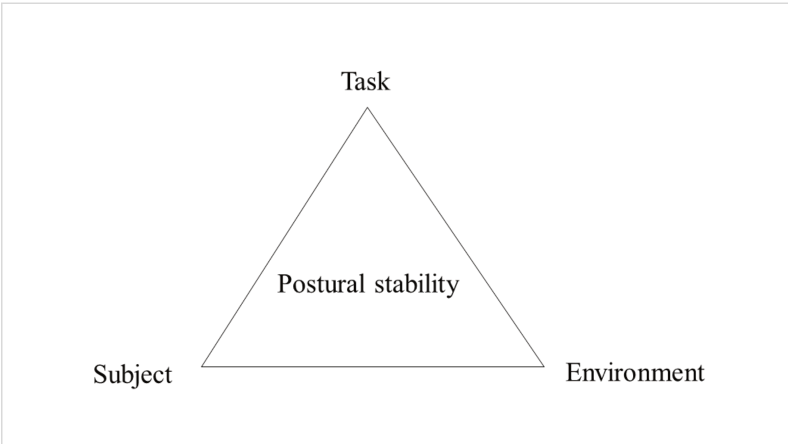

Figure 1: Emergence of movement behavior (here postural stability) from the interaction of the environmental, task-inherent and subject-related factors
Adapted from [Newell, 1986]

In our experiments, we have manipulated the different mentioned constraints in order to explore how sensory supplementation influences postural stability, especially in higher age, by 1) controlling the sensory cues available to the CNS (environmental constraints), 2) using more or less challenging postural tasks (task-inherent constraints) and 3) exploring the effect of age of different groups of participants (subject-related constraints).

1.1.2. Variables extracted from center of pressure trajectories to assess postural stability

A common measure of postural stability in sitting, quiet and perturbed stance is the displacement of the COP over time, which can be recorded by a force platform [Prieto et al., 1996, Rougier, 2008]. In the following, we will introduce the different variables extracted from COP trajectories used for data analysis in the present work. Note that the choice of variables followed the tested hypotheses.

Classical variables of interest assess the variability of the COP positions (RMS), the range of the COP positions (range), the mean velocity of the COP trajectory (MV) and the area covering the planar COP displacements (area). The RMS is calculated as the square root of the mean of the squared COP-position values and the range by subtracting the greatest from the lowest COP-position value. Both can be calculated in the AP and ML directions. The MV is estimated by dividing the total length of the COP trajectory by the duration of the record. To this aim, the total length can be estimated by the sum of the Euclidean distances between two successive COP positions [Raymakers et al., 2005]. The area of the COP displacements is currently estimated by fitting an ellipse encompassing 95% of the planar COP displacements by means of principle component analysis [Duarte and Zatsiorsky, 2002]. In most studies, individual data of different trials of each condition are calculated and then averaged so that the participants' means can be used for statistical analysis.

The COP trajectories can also be subjected to a Fast Fourier Transform in order to determine the frequency components of the body sway. Power spectra of different trials of each condition are currently averaged to obtain an individual spectral signature, which is used for further analysis. Classical variables of interest in the frequency domain are the mean total power (MTP) and the mean power frequency (MPF, [Holden et al., 1994, McClenaghan et al., 1996]). The MTP is calculated as the sum of all power values of the spectral signature and represents the mean power of the signal. Higher MTP of the frequency spectrum have been observed during upright standing in older adults when compared to their younger counterparts [McClenaghan et al., 1996]. The MPF is calculated as the sum of each power value of the spectral signature multiplied by the corresponding frequency and then normalized by the MTP [Holden et al., 1994]. It corresponds to the frequency that, on average, characterized the most power of the signal. Higher MPF have been observed during upright standing in the postural sway of older adults when compared to younger adults, presumably resulting from increased muscle activity and ankle stiffness [Carpenter et al., 2006, Vieira et al., 2009].

In the present work, a particular focus was on the effect of haptic supplementation on postural control mechanisms that operate with different time delays. It is generally accepted that postural sway results from two main sources: 1) very short-term corrections, resulting from changes in intrinsic visco-elastic properties of the muscles and 2) long-term corrections that are based on the use of sensory feedback. These latter corrections imply time delays due to signal transmission and processing. To infer these two mechanisms from COP trajectories, a suitable COP analysis - the stabilogram diffusion analysis (SDA) - has been proposed for postural control of upright standing by Collins and De Luca (1993, for details). It has also been applied to postural control of sitting [Cholewicki et al., 2000, Radebold et al., 2001, Silfies et al., 2003]. Based on the time-series of COP positions, the mean squared displacements of the COP are determined for data points separated by various time intervals. In stabilogram diffusion plots, the mean squared displacement is plotted against corresponding time intervals (Figure 2). The plots of different trials of each condition are currently averaged, serving as an individual resultant plot for further analysis. With increasing time intervals, the mean squared displacement increases in these plots. However, the slope classically exhibits an abrupt change that is, it is different for shorter and longer time intervals. The critical point (x-coordinate: critical time interval (CPs) and y-coordinate: critical mean squared displacement (CPmm²)) indicates the region of time intervals where the slope significantly changes. It separates, thus, the short-term and long-term region of the plot.

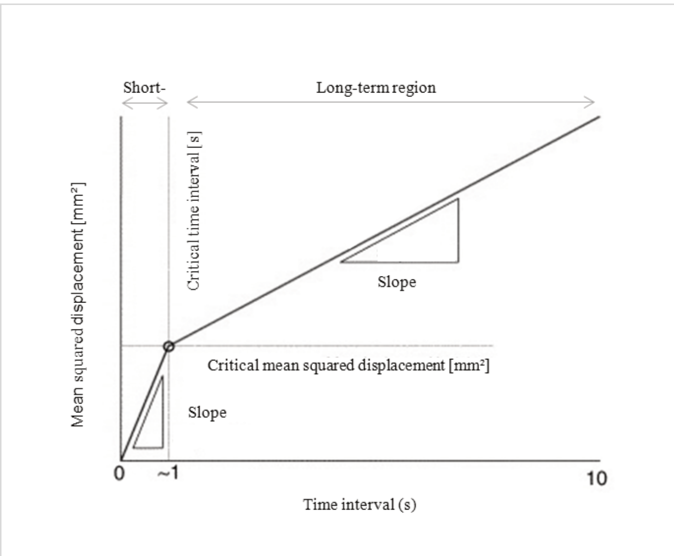

Figure 2: Scheme of a stabilogram diffusion plot
Adapted from [Norris et al., 2005]

The slopes of regression lines fitted to the two regions of the (linear-linear) plots are the short-term (Ds) and long-term diffusion coefficients (Dl). They are interpreted as indicators of the open-loop and closed-loop stochastic activity of the COP, respectively. According to Collins and De Luca (1993), higher short-term and long-term diffusion coefficients refer to higher stochastic activity and can be explained by higher activation of postural muscles needed to control a rather unstable system. The SDA, thus, extracts physiologically meaningful information from the COP trajectories that are associated to the steady-state postural behavior (open-loop) and to the time-demanding postural feedback control mechanisms (closed-loop).

1.1.3. Biomechanical models of standing and sitting posture

Since the human body is a complex multi-joint system, the question arises of how erect, upright balance can be maintained in both standing and sitting tasks. Classically, in the literature on standing postural control, different kinds of coordination patterns between body segments (i.e., essentially trunk and lower limbs) have been observed depending on the type of perturbation applied to the postural system. Without being perturbed or in response to smaller translations of the support surface, single-joint coordination patterns have been frequently observed to maintain upright stance (ankle strategy), whereas in response to large translations of the support surface, multi-joint coordination patterns dominated (hip strategy).

Thus, in unperturbed situations, a commonly accepted assumption is that both standing and sitting postures can be modelled as an inherently unstable single-joint inverted pendulum rotating around the ankle [Maurer and Peterka, 2005, Peterka, 2000] or hip [Cholewicki et al., 2000, Reeves et al., 2007], respectively. In this perspective, one considers that to maintain postural stability, the CNS primarily achieves active control of only one degree of freedom (DoF, ankle or hip joint, respectively) in combination with the stiffness provided by corresponding passive musculoskeletal structures. This single-joint inverted pendulum model is assumed to rely on a simple, direct relationship between muscle activation and behavioral output variables (e.g. COM, COP or head). During upright standing, COP trajectories result from corrective torque exerted by dorsal and plantar flexion in the sagittal plane and by hip abduction and adduction in the frontal plane [Winter et al., 1996]. During sitting, they result from corrective torque exerted by hip and intervertebral joint adjustments in the sagittal plane and by intervertebral joint adjustments alone in the frontal plane [Silfies et al., 2003]. The single-joint inverted pendulum model is currently considered as the reference model in the literature for unperturbed balance and it has inspired most postural control studies [Cholewicki et al., 2000, Maurer et al., 2006, Peterka, 2002, Reeves et al., 2007].

However, as for most of our coordinated movements [Bernstein, 1967], successful postural stability during perturbed upright stance may require coordinated control of several body components [Hsu et al., 2007, Kiemel et al., 2008, Ting, 2007]. In particular, in dynamic upright standing situations, pure ankle control may not suffice to keep the COM above the BOS. Instead, a strategy that consists of the use of two DoFs (ankle and hip) seems to be more appropriate. This strategy corresponds to an anti-phase coordination pattern between the lower and the upper body segments [Horak and Nashner, 1986, Horak and Macpherson, 1996] that more effectively corrects the COM position. Perturbed balancing can be modelled as a multi-joint model [Alexandrov et al., 2005, Hsu et al., 2007] that provides a realistic idea of complex postural behavior.

The findings by Hsu et al. (2007) and Creath et al. (2005) illustrate the subtle differences in the different points of view available in the literature of biomechanical postural models. Challenging the assumption that only the ankle strategy is used by the CNS to achieve unperturbed upright stance, Hsu et al. (2007) showed that, even in an unperturbed situation, several joints (in addition to the ankle) exhibit noteworthy variance. The authors hypothesized that the CNS coordinates redundant DoFs in order to have limited effect on the task-related variable (COM position). In support of this hypothesis, owing to the spectral analysis of inter-segment body motion, Creath et al. (2005) showed that two modes of coupling between legs and trunk simultaneously occurred during unperturbed stance. Specifically, these two segments were found to oscillate in-phase with respect to each other for low frequency ranges (i.e., < 1Hz) and anti-phase for higher frequency ranges (i.e., > 1Hz) (see also [Zhang et al., 2007]). These examples show that different biomechanical postural models can account for the biomechanical structure that is to be controlled in unperturbed balance situations. From a kinematic point of view, all DoFs along the longitudinal axis of the body (more than just the ankle joint) are engaged in postural control during quiet balancing. Postural control may exploit joint redundancy through the use of different coordination patterns between the ankle, knee, hip and spine that are assembled as a function of the environmental, task-inherent and subject-related constraints.

In spite of these findings, most authors assumed that the single-link inverted pendulum model constitutes an acceptable model in a wide range of standing [Maurer and Peterka, 2005, Peterka, 2000] and sitting postural situations [Cholewicki et al., 2000, Reeves et al., 2007].

Consequently, in the present work, we have considered this model as the reference model for the study of multisensory integration during quiet standing (see studies I and II, chapters 3 and 4, respectively) and sitting (see study III, chapter 5). When studying perturbed upright stance (see studies IV and V, chapters 6 and 7, respectively) our analysis of coordinative patterns between the different body segments were based on the model of a two-link inverted pendulum (ankle and hip).

1.1.4. Postural strategies: voluntary selection of motor programs or constraint-related self-organizing patterns

Still, the question remains of how the CNS controls the different DoFs of the single or two-link inverted pendulum when constraints inherent to the environment, task or subject change (see Newell (1986)'s model above, chapter 1.1.1.). In this respect, postural strategies (i.e., the ankle and hip strategy), have been classically interpreted as the result of voluntary selection of a prestructured, memorized central motor program managing postural constraints in order to maintain upright stance [Horak and Nashner, 1986, Nashner, 1977]. However, a different interpretation was proposed on the basis of the dynamic properties of postural strategies observed in a visual tracking task during upright standing [Bardy et al., 1999, Bardy et al., 2002]. Participants were instructed to sway in order to track a visual stimulus, moving back and forth. With increasing stimulus frequency within a trial, participants spontaneously switched from an in-phase between the body segments (ankle strategy) to an anti-phase pattern (hip strategy). Drawing a parallel with the dynamic patterns observed in numerous multi-segmental action systems (which were conceptualized by Kelso and collaborators, 1984), 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 or visual tracking task). Accordingly, even if the CNS manages the coalition of postural constraints by adopting different strategies, it is still unclear whether these strategies result from the selection of central motor programs, whether they emerge as self-organizing patterns, or both.

1.1.5. Sensorimotor control of upright posture

1.1.5.1. A general model of postural control (sitting and standing)

Even though different biomechanical systems are involved in the standing and sitting postural tasks, Kiemel et al. (2008) and Reeves et al. (2007) have proposed similar solutions to the problem of how postural control is achieved by the CNS in the two tasks (Figures 3 and 4, respectively). Both models include two components contributing to the system's stability - a plant and a controller.

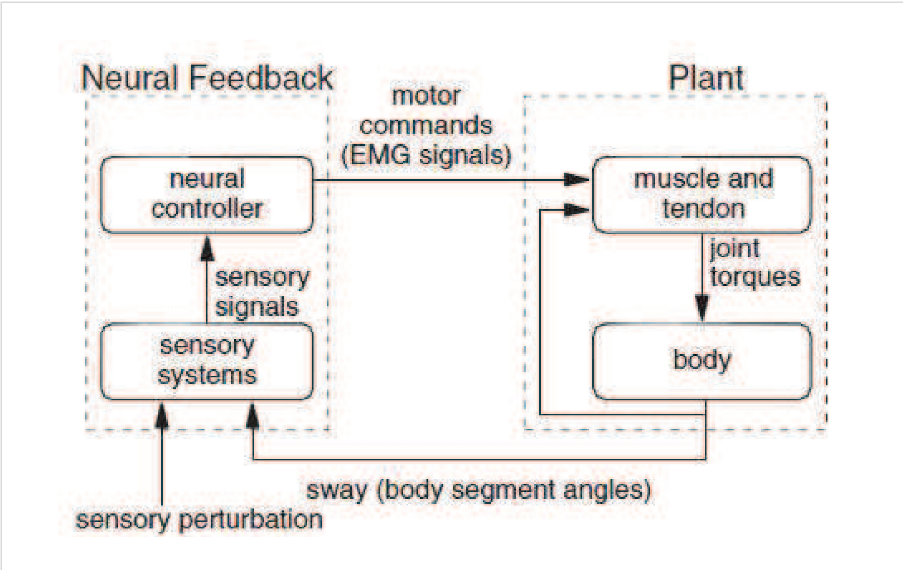

Figure 3: Postural feedback control model for upright standing
Adapted from [Kiemel et al., 2008]

The plant represents the biomechanical structure that has to be controlled. The controller generates the input to the plant needed to achieve the desired output, corrective postural muscle activation to achieve upright standing or sitting. For this purpose it is provided with a variety of signals (proprioceptive, vestibular and visual) about the spatial orientation and motion of the plant.

Both the sitting and standing postural control models are inspired by control theory, and their 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 and require time delays due to signal transmission and processing and 2) intrinsic, very short-time corrections, resulting from changes in visco-elastic properties of the muscles, which do not require changes in neural activation.

In the present work, we took advantage of common control principles at work during standing and sitting to explore the functional role of haptic cues in postural feedback control.

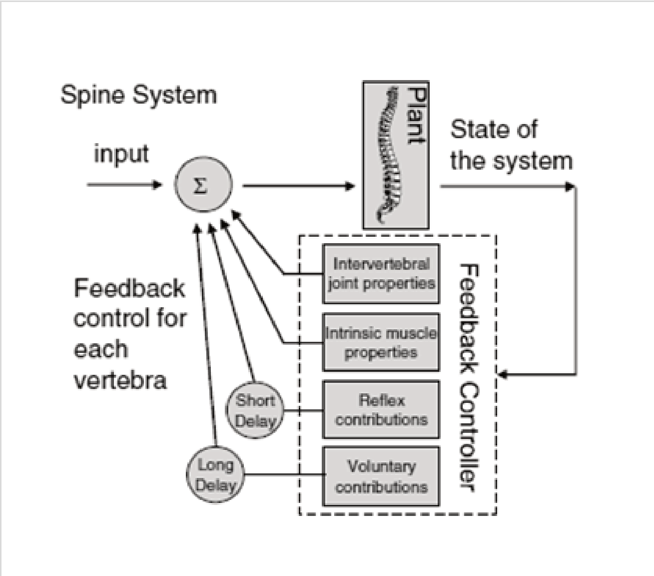

Figure 4: Model of the spinal feedback controller
Adapted from [Reeves et al., 2007]

1.1.5.2. The role of sensory feedback

Feedback mechanisms involved in postural control imply time delays due to signal transmission and processing. This means that the neural controller receives sensory inputs about the spatial orientation and motion of the body with respect to gravity and the environment with a given time delay before corrective motor commands can be elaborated and then corrective torque can be generated (Figure 5, [Peterka, 2002, Maurer and Peterka, 2005, Maurer et al., 2006, Kiemel et al., 2008, Mahboobin et al., 2009]). The different sensory cues used for this purpose are derived from different signals, e.g. those related to 1) the position of objects in the visual environment, 2) the linear or angular acceleration of the head as well as its orientation relative to gravity, or 3) the distribution of forces applied to the plantar sole, the muscle length or velocity of contraction (see chapter 1.1.5.3, for further details). Therefore, the cues are associated to a specific frame of reference for spatial orientation. In order to integrate them and to estimate the body orientation and motion, the different sensory cues may require transformation to a common consistent frame of reference [Jeka et al., 2000, Mahboobin et al., 2009].

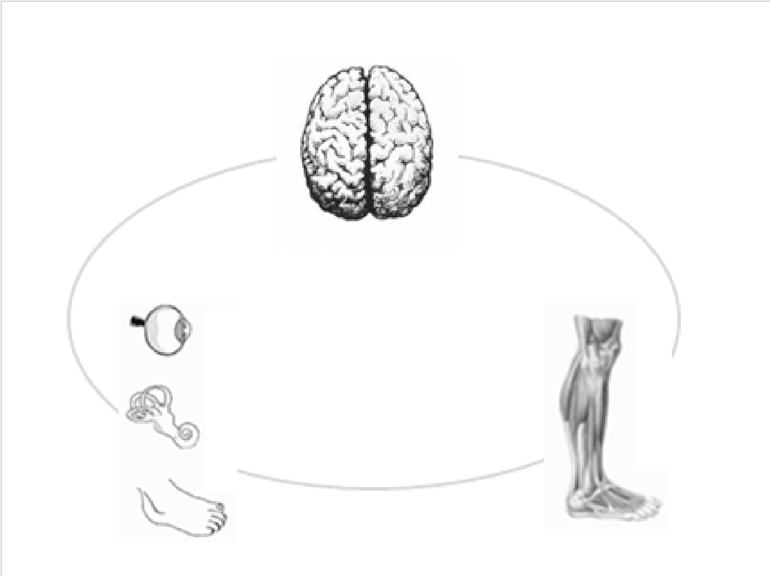

Figure 5: Schematic of the continuous interactions during postural control between the different sensory systems, the CNS and the muscular effectors

Collins and colleagues [Collins and De Luca, 1993, Collins et al., 1995, Collins and De Luca, 1995a, Collins and De Luca, 1995b] proposed a special kind of framework for postural feedback control. The authors claimed that the CNS is continuously receiving sensory cues to achieve feedback control mechanisms but that very small deviations (below sensory threshold) do not require closed-loop control but rather open-loop control mechanisms for postural corrections. This hypothesis contrasts with that proposed by Peterka (2002). Sensory thresholds reduce the amount of information flow to be processed by the CNS (only cues beyond sensory threshold) and so Collins and colleagues' proposition simplifies the multisensory integration problem.

Similar to postural control models related to upright standing, studies in the domain of sitting posture suggested that postural stability during sitting was achieved through 1) tonic baseline trunk muscle activation to stiffen the trunk in an open-loop manner, and 2) feedback-based phasic muscle activation [Zedka et al., 1998, Masani et al., 2009]. Masani et al. (2009) put forward that the phasic, direction-specific muscle activation developed in response to surface perturbation is presumably and primarily based on sensory feedback, such as pelvis proprioception and cutaneous cues from buttocks and thighs.

In summary, sensory feedback from multiple sources and their integration in the CNS play a key role in the control of standing and sitting balance. The efficacy of sensory integration and, thus, postural control depend on the intactness of the different peripheral sensory systems (chapter 1.1.5.3.) and the central processing by the CNS (chapter 1.1.5.4.), both of which can be altered during normal or pathological aging (chapters 1.3.2. and 1.3.3.).

1.1.5.3. Sensory systems involved in postural control

During the last 20 years, experimental manipulation of different sensory inputs has permitted to assess the contribution of each sensory modality and to study multisensory integration during postural control in upright standing situations (e.g., sensory organization test [Horak, 1987]). This has scarcely been done in sitting situations (see [Silfies et al., 2003], for exception).

Each sensory modality provides the CNS with a flow of sensory cues that is associated with a specific frame of reference. Specifically, visual inputs provide a reference for verticality and for self-motion by detection of optic flow. One usually considers that proprioceptive inputs provide a reference for (the quality of) the support surface due to sensory cues about joint position, muscle length, velocity of contraction and relative movements of body segments. Maurer and colleagues [Cnyrim et al., 2009, Maurer et al., 2000, Maurer et al., 2006] argued that the CNS might also extract information about the COP motion from tactile mechanoreceptors in deeper structures of the foot, complementary to the information from mechanoreceptors in muscles and joints. Referring to its functional role of informing the CNS about the gravitational ground reaction forces and their spatial distribution underneath the feet when a body leans on a stable support surface, this force-related information was called “somatosensory graviception”. It was therefore suggested that force-related sensory cues should be included in postural control models [Cnyrim et al., 2009, Maurer et al., 2000, Maurer et al., 2006]. The vestibular system provides the CNS with a gravito-inertial reference [Shumway-Cook and Woollacott, 2007] according to angular acceleration (semi-circular canals) and linear acceleration and tilt of the head relative to gravity (otholithic system). Moreover, different reflexes help maintain stable posture, such as the vestibulo-ocular (visual fixation during head movement) and the vestibulo-spinal reflexes (trigger of muscle activity in neck, trunk and extremities). As combining different sensory information may engage transformations to a common frame of reference, a current challenge of postural control research is to understand how the CNS combines the orientation cues of different sensory modalities to estimate body position and motion [Jeka et al., 2000, Mahboobin et al., 2009]. The present work is consistent with this line of research as it aimed to understand 1) if haptic cues are integrated by the CNS in the same way than the commonly used sensory sources (visual, proprioceptive and vestibular), and 2) if compensatory mechanisms are achieved between commonly used sensory cues and haptic cues.

1.1.5.4. Mechanisms of multisensory integration

Even though postural regulation in constant sensory environments has been predominantly considered as a linear process (i.e., constant sensory weights, [Fitzpatrick et al., 1996, Oie et al., 2001]), several authors argued for the role of nonlinearities in multisensory integration processes (i.e., response saturation, different weights attributed to sensory stimuli) that appear when sensory stimuli changed [Jeka et al., 2000, Mergner and Rosemeier, 1998, Peterka, 2002, van der Kooij et al., 1999].

For instance, Ting (2007) proposed that the simple summation of the different sensory channels is insufficient for postural control and that an internal model that captures their combination is required. Internal estimates that are, reconstructions of external stimuli, are supposed to be more easily manipulated for memory and movement planning [Maurer et al., 2006]. In a different perspective, Peterka [Peterka, 2002, Peterka and Loughlin, 2004] proposed the "independent channel model". In contrast to earlier hypotheses of constant sensory weights [Fitzpatrick et al., 1996], Peterka (2002) concluded that dynamic stimulus-dependant changes occur in the sensory contribution to postural control (sensory reweighting) in healthy adults under a variety of environmental conditions. According to this model, sensory thresholds are nonlinear, 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. This hypothesis must be considered in the investigation of haptic supplementation. Indeed, the question arises of whether low-intensity stimuli from fingertips (due to the task of lightly touching) may be effective to improve postural control, considering the age-related declines in the sensitivity of cutaneous receptors in the fingertips (increased sensory thresholds). A technological solution could be used in this respect (e.g., vibratory noise applied to the touching fingertips) in order to “decrease” sensory threshold due to higher age. This so-called stochastic resonance technique has been formerly found to enhance the effectiveness of a LT on a stable support by activating not only supra-threshold mechanoreceptors but also sub-threshold ones via vibration [Magalhães and Kohn, 2011].

Experimental manipulation based on a perturbation or deterioration of one or more sensory cues (e.g., galvanic stimulation [Séverac Cauquil et al., 1998], vibratory stimulation of the calf muscle [Gomez et al., 2009], eyes closure [Jeka and Lackner, 1994]) generally results in an increase of postural oscillations. However, the CNS can employ (to a certain extent) compensatory mechanisms via sensory reweighting and obviate direct functional consequences. Exploiting the concept of sensory reweighting, Jeka and colleagues [Allison et al., 2006, Jeka et al., 2000, Oie et al., 2001] 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 and inter-sensory reweighting 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 sensory modalities. Even though mechanisms of sensory reweighting need further investigation, promising findings about the instantaneous stabilizing effect of haptic supplementation (light touch), the effect of sensory enhancement (stochastic resonance or galvanic vibration) and sensory substitution (electrotactile biofeedback) do give weight to the hypothesis about dynamic and nonlinear interactions within and between different sensory modalities for postural control of young and older adults. On the basis of feedback models by Peterka (2002), Jeka and colleagues [Allison et al., 2006, Jeka et al., 2000, Kiemel et al., 2008, Oie et al., 2001] and Reeves et al. (2007), we will develop our statement about the stabilizing effect of haptic supplementation due to multisensory integration and reweighting during sitting and standing posture.

1.2. Haptic supplementation

The term “haptic sense” used in the present work has been introduced two decades ago in the theoretical context of postural control by Jeka and Lackner (1995). It refers to the perceptual sense which combines cutaneous and proprioceptive inputs from mechanoreceptors embedded in skin, muscles and joints of the arm and fingers (or other parts of the body) while touching or manipulating an object. In this context, haptic supplementation is a means of providing the CNS with additional cutaneous and proprioceptive cues via the light contact between a body part and the environment during a postural task. In the following, we present the different paradigms that have been used in the literature to test the effect of haptic supplementation. The experimental paradigm employed in the present work (chapter 2.) is highly inspired by the different existing paradigms and constitutes a combination of a LT on a mobile support (chapters 1.2.1., 1.2.3. and 1.2.4.) and a passive stimulus (chapter 1.2.2.), which have both been proven to provide sway-related orientation cues and to improve postural stability.

1.2.1. Light-touch paradigm (fixed support)

In their seminal works, Jeka and Lackner (1994, 1995) demonstrated the functional role of supplementary haptic information provided by a LT during postural control. The light-touch paradigm consisted in an active touch (< 1 Newton (N)) of the index finger on a stationary surface (Figure 6). 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 [Holden et al., 1994]. Subsequently, several studies have confirmed the benefit of haptic cues to decrease postural sway [Baccini et al., 2007, Dickstein et al., 2001, Krishnamoorthy et al., 2002, Rabin et al., 2008]. Baccini et al. (2007) found that a LT was more efficient for older than for young adults with eyes closed (EC). Moreover, it has been shown that older patients with peripheral neuropathy [Dickstein et al., 2001] and patients with loss of vestibular function [Lackner et al., 1999] benefit from haptic supplementation via a LT by improving postural stability. Concerning theoretical interpretations of the benefits of haptic supplementation, Jeka and Lackner (1994, 1995) suggested that touch on a stable support surface provides a precise reference frame to the participants facilitating the detection of self-motion and body position in the environment and, finally, permitting adaptive postural corrections.

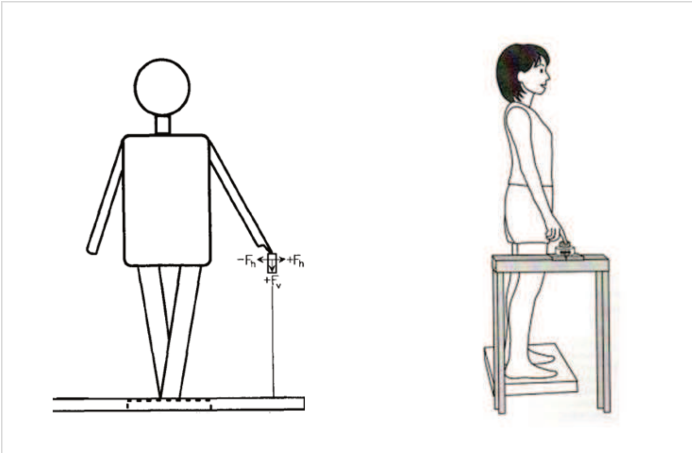

Figure 6: Two examples of a classical light touch on a fixed support
Adapted from [Jeka and Lackner, 1994] (on the left) and [Kouzaki and Masani, 2008] (on the right)

Afterward, results suggested 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 and Lackner, 1994, Krishnamoorthy et al., 2002, Lackner et al., 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 and Lackner, 1994, Jeka and Lackner, 1995, Lackner et al., 2001]. Rabin et al. (2008) showed that, in order to be effective, transient fingertip contact forces should be completed by congruent arm proprioception. This interpretation was based on the fact that perturbation of haptic cues during the LT by vibration of the biceps muscle lowered the stabilizing effect but not restriction of the arm movements. The authors concluded that incongruent information arising from mechanoreceptors of the joints and muscles of the arm (during vibration) results in a biased representation of the body position and thereby in a higher postural instability.

1.2.2. Passive-stimulus paradigm

Another paradigm of haptic supplementation has been examined in several studies showing a comparable effect on postural stability. It consisted of a passive stimulus (PS) applied to the skin of various body parts during quiet stance. During the PS, a piece of rough surface was kept in light contact with the participants' skin during balancing trials, which created movements of the swaying body relative to the stationary rough surface (Figure 7). It has been found that this kind of haptic information (shear forces) enhanced postural stability in young and older adults. In the study by Rogers et al. (2001), three groups of participants (young adults, older adults and diabetic patients) were tested during upright standing with or without the PS. Those participants with greater postural sway (older adults and diabetic patients) have been found to benefit more from the PS than the most stable participants (young adults) [Rogers et al., 2001]. In addition, the PS has been proven to be most beneficial for postural stabilization the higher the stimulus was applied to the body. Greater stimulus amplitudes arose when the stimuli were applied to higher parts of the body (shoulder) when compared to lower ones (knee).

Both procedures, the LT and the PS, gave rise to similar interpretations. Overall, corresponding results suggested that the CNS uses the transient sway-related changes in contact forces and proprioception that arise from the light contact of a part of the body with a stationary support to improve self-motion perception and postural stability.

In the context of the present work, we aimed at combining the main features of these two paradigms (PS and LT) to a mobile-stick experimental paradigm: the light contact between the body and the environment via a mobile stick and the passive stimulus at the end of this stick. In this situation, the shear forces (created in passive-stimulus studies at the skin of the shoulder, knee [Rogers et al., 2001] or ankle [Menz et al., 2006] by body movements relative to a stationary rough surface) would be created at the level of the fingertips by the sway-related stick movement on the ground. We hypothesized that the resistance induced by the scratching stick as the result of body sway would inform the participants about their body motion and would thereby enhance postural stability. The rational underlying the use of the present mobile-stick paradigm is detailed (chapter 2.).

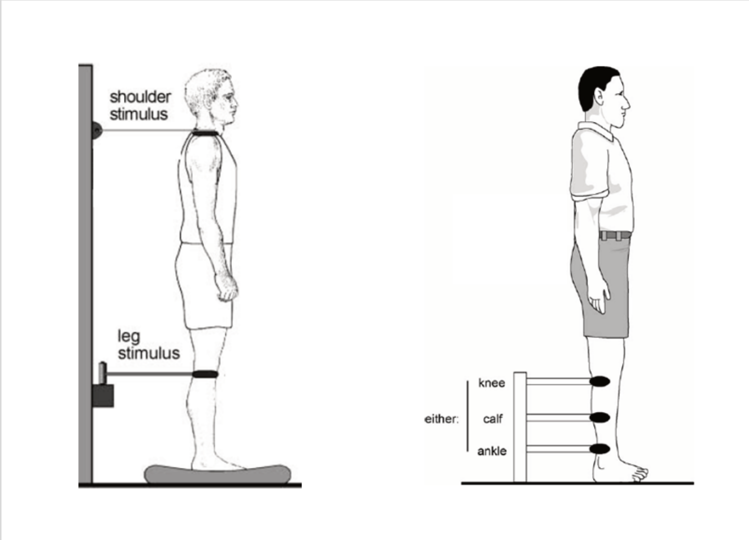

Figure 7: Two examples of a classical passive stimulus applied by a rough stationary surface to the skin of the oscillating body
Adapted from [Rogers et al., 2001] (on the left) and [Menz et al., 2006] (on the right)

1.2.3. Light-touch paradigm (mobile support)

Few works have systematically explored the benefit of haptic cues on postural stability by the use of a specifically dedicated mobile-stick experimental paradigm (see below [Jeka et al., 1996], for a noticeable exception). Nevertheless, the results observed in several studies might lead to hypothesize that a LT on a mobile support could provide useful orientation cues to control body oscillations [Boonsinsukh et al., 2009, Jeka et al., 1996, Jeka, 1997, Krishnamoorthy et al., 2002, Lackner et al., 2001].

Krishnamoorthy et al. (2002) observed a stabilizing effect of a mobile support that is, a hand-held handle linked via a pulley system to a 3-kg-weight (Figure 8). In this situation, handle displacements and transient horizontal forces arising at the level of the handle were sway-related and helped decreasing body sway. Comparing the effect of this mobile support to fixed ones, the authors observed that a maximum gain of postural stabilization could be exclusively obtained by the use of a stable light-touch support. However, even in the absence of a fixed reference point, that is, when touching the handle of a pulley system, sway-related transient contact forces based on tissue deformation can be large enough to help orientate the body and decrease body sway.

Figure 8: Mobile light-touch support: hand-held handle linked via a pulley system to a weight
Adapted from [Krishnamoorthy et al., 2002]

Krishnamoorthy et al. (2002) explained their results by the existence of different mechanoreceptors in the skin, which provide sensory cues during touch to inform, on the one hand, continuously about the position of the support (slowly adapting receptors) and, on the other hand, about the direction, amplitude and velocity of the body oscillations based on tissue deformation (slowly and fast-adapting receptors in combination). A similar conclusion, underlining the importance of sway-related information, can be drawn from the results observed by Reginella et al. (1999), which showed that erroneous information provided by an oscillating sway-referenced light-touch support had a destabilizing influence on posture.

These findings suggested that the use of a mobile support might provide functional haptic information to stabilize posture when sufficient sway-related transient forces are present. Two studies need to be cited, that support the above-mentioned hypothesis and that approach certain aspects of a mobile-stick experimental paradigm. By fixing the entire arm during a LT, Rabin et al. (2008) observed small amplitude movements of the finger on a stationary support surface that caused occasional disruptions between the point of contact and the light-touch support. Results showed that, even though the finger slipped relative to the stable surface (< 3 N) a stabilizing effect on posture was still observed. Thus, fingertip movements do not preclude sway-related information from being detected and used for spatial orientation of the body, which is a very similar observation than previously described concerning the PS. In contrast to the "fixed reference point" interpretation, one could claim that the functional orientation cues are gained, in this case, within a certain stable but limited spatial area. Another study by Lackner et al. (2001) illustrates the above-mentioned hypothesis in the context of postural stabilization resulting from a LT on flexible filaments. The authors furnished the circular extremity of vertically mounted flexible filaments as a non-rigid light-touch support. To be precise, the filaments were slightly deformable but did not move beyond certain spatial limits/ a certain spatial region. Even though the stabilizing effect resulting from a LT on flexible filaments was less effective than a LT on a rigid surface, the authors observed a significant increase in postural stability in both situations. Accordingly, Lackner et al. (2001) claimed the importance of a fixed reference region that has to be provided by the mobile light-touch support in order to make useful orientation cues available. Taken together, the above-mentioned findings encouraged us to study the stabilizing effect of a mobile stick in a more detailed way. In a sense, sway-related information through the stick movements on a small region on the stable ground, in the present work, would also be gained from a fixed reference region.

1.2.4. Light touch through the use of a mobile stick

In view of both, its theoretical interest and its potential applications in the domain of mobility aids, it should be demonstrated that haptic supplementation is also effective when the support is mobile, oscillating with the swaying body or moving in space. Indeed, although several authors emphasized the importance of a hand-held cane to provide haptic supplementation and functional orientation cues [Bateni and Maki, 2005, Boonsinsukh et al., 2009, Jeka et al., 1996, Jeka, 1997], 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 cane. The few existing literature about this topic will be addressed in the following.

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 and were instructed to lightly grip the handle of a cane (< 2N). Two orientation conditions – vertical and slanted in the ML direction (70° with respect to the horizontal) – of a cane, pivoting around its fixed lower 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 does not move in the direction of the participant's body oscillations. Subsequently, it leads to functional sway-related contact forces as the result of the resistance of the inclined cane against medio-lateral body sway. This conclusion is consistent with other results showing that stabilization resulting from a LT was most effective when force changes are generated in the plane of greatest instability [Rabin et al., 1999]. However, a limitation of Jeka et al. (1996)'s study was that the slanted cane was fixed on the ground. Consequently, a potentially helpful DoF (in view of a potential portable haptic device) was frozen. Additionally, in the slanted cane condition, the handle of the stick appeared to be stationary and could consequently be considered as a fixed rather than a mobile support. Moreover, no information was given by Jeka et al. (1996) about the effect of the slanted cane in the AP direction, in which the handle was actually free to move and, consequently, mobile.

Until now, the question of whether and how sensory cues can be delivered by a portable cane during locomotion has been only scarcely studied. For instance, Boonsinsukh et al. (2009) have investigated the role of a cane as a mediator of sensory information used in a "light" manner (< 4 N) during locomotion of stroke patients. The results showed increased ML stability through a "light" cane use during patients' locomotion and higher muscle activity of the paretic leg due to a "light" cane use as compared to a "force" cane use condition (~ 50 N). To our knowledge, Boonsinsukh et al. (2009)'s study is the only one who applied the idea of a LT to a locomotor task while using a cane to provide haptic cues. Therefore, this study represents a threefold exception in the domain of the LT as the authors manipulated 1) environmental (haptic cues via the use of a portable cane), 2) task-inherent (haptic cues provided during locomotion) and 3) subject-related constraints (use of haptic cues by stroke patients). However, in this study, participants were free to individually choose their "light" cane use, for example, intermittent cane use or constant cane contact with the ground. Even though almost all patients used the cane in a "light" intermittent manner we think that the authors might not have controlled sufficiently for the type of haptic cues that were provided. Another limitation of this study was that the effect of the "light" cane use on stroke patients could be specific to this group of patients with motor problems and might not be generalizable to other populations. Despite the fact that this study showed a beneficial effect of cane-provided haptic cues in stroke patients, a systematic experimental manipulation of fixed and mobile light-touch supports is actually missing in the literature of haptic supplementation. Such systematic investigation should test the effect of haptic cues mediated by a mobile support in various postural tasks (quiet and perturbed stance, sitting) and in healthy young and older adults.

1.2.5. Light touch during complex postural tasks

In addition to the study by Boonsinsukh et al. (2009), we identified two types of studies in the light-touch literature: 1) testing the effect of a LT, while increasing the mobility of the light-touch support [Jeka et al., 1996, Krishnamoorthy et al., 2002, Lackner et al., 2001] and 2) testing the effect of a LT, while increasing the complexity of the postural task, as for instance during perturbed standing or locomotion (see below [Dickstein and Laufer, 2004, Fung and Perez, 2011, Ivanenko et al., 1999, Kazennikov et al., 2005]). As presented above (chapter 1.2.3.), in the first type of studies, a stable upright stance situation was used and only environmental constraints were manipulated (haptic cues via the use of mobile support). As will be presented in the following, in the second type of studies, light-touch supports had a very limited mobility (fixed support) and only task-inherent constraints (haptic cues provided during complex postural tasks) were manipulated.

In contrast, the experimental paradigm used in the present work, aimed to manipulate both environmental and task-inherent factors before applying the mobile-stick experimental paradigm to locomotion.

1.2.5.1. Light touch during perturbed upright stance

As mentioned above, few studies examined the effect of a LT during perturbed upright standing or locomotion. Those interested in perturbed upright stance tested the effect of a LT on postural stability of young participants standing on a rocker board (1 DoF in the AP direction [Hausbeck et al., 2009, Ivanenko et al., 1999, Kazennikov et al., 2005, Kazennikov et al., 2008]). These studies used fixed or mobile light-touch supports (i.e., a classical fixed support, small loads held in front of the body or lightly-touched canes). The stabilizing effect of two kinds of haptic cues was tested in these studies: 1) changes in inertial forces by holding an object in the hand without contact with the environment [Hausbeck et al., 2009, Kazennikov et al., 2008] or 2) changes in haptic cues provided by the light contact with a fixed support in the environment [Ivanenko et al., 1999, Kazennikov et al., 2005].

The study by Hausbeck et al. (2009) was the only one employing a cane to provide sensory cues during perturbed standing. The authors tested the stabilizing effect of a LT of canes of different stability in a perturbing visual environment. The stability of the canes varied: from lowest (horizontally-held cane) to medium (rocker cane that knocked over at > 0.4 N) to highest (quad cane that knocked over at > 0.4 N). The horizontally-held cane provided changes in inertial forces at the level of the hand through its weight, while the two others provided haptic cues from a LT. The rocker-cane condition (vertical cane mounted to a small hemisphere) was very similar to the vertical-cane condition tested by Jeka et al. (1996) as the cane pivoted vertically about a relatively stable point, whereas the handle of the cane was free to move. The quad-cane condition provided changes in cutaneous and proprioceptive cues from the LT on a fixed support. The authors found that the perturbation induced by the visual environment (which caused an increase in COM and angular displacements of ankle and hip on the rocker board) could be compensated by all three kinds of haptic cues. Indeed, larger stabilizing effects were observed with increasing stability of the cane (see [Krishnamoorthy et al., 2002, Lackner et al., 2001], for similar interpretation about a hierarchical effect). These results suggested that the CNS can disregard unreliable visual cues due to additional orientation cues provided by a cane in order to improve the control of the perturbed posture. Notably, no postural stabilizing effect was observed in the horizontal-cane condition, when vision was untroubled. Conversely, when troubled, gripping the horizontally-held cane led to postural stabilization. These results suggested that a more perturbing postural situation may create more easily detectable (or necessitate the use of) transient inertial forces that appear to be undetectable or not functional when vision is untroubled. This might suggest that the CNS relies more on information provided by transient inertial contact forces, even small, in more demanding or sensory conflicting situations.

Similarly, Kazennikov et al. (2008) tested the stabilizing effect of changes in inertial forces in the hand while holding a small load (200 g, 500 g or 1000 g) in front of the body standing on a rocker board. Holding a 1000-g-load reduced the sway of the rocker board controlled by the participants. The results suggested that additional orientation cues (mainly related to inertia/

acceleration) can be used by the CNS to better control the perturbed posture on the rocker board.

Ivanenko et al. (1999) observed that the destabilizing effect of neck or Achilles tendon vibration was minimal when standing on a rocker board, whereas it increased when a LT (< 3 N) of a fixed support was simultaneously performed. The authors suggested that the CNS decreases the weight attributed to proprioceptive cues when perturbed by a rocker board. Performing a LT changes again the contribution of sensory sources to postural control, which increases the weight attributed to proprioceptive and cutaneous cues for postural stabilization. In contrast to these findings, Kazennikov et al. (2005) observed a less destabilizing effect of calf muscle vibration applied while standing on a rocker board when simultaneously performing a LT (< 1 N) on a fixed rail. This gain in stability through the LT was more pronounced when the platform underneath the rocker board was stationary than when it moved very slowly back- and forward (finger slid over rail as the platform moved). The authors concluded that 1) the orientation cues provided by the LT are more important than the artificially produced afferents from the ankle joint through vibration, and that 2) the reliability of the haptic cues determines whether or not they can be used to build a reference frame for postural control. In this perspective, it was hypothesized that haptic cues from a sliding finger are less appropriate to build such reference frame and, thereby, lead to a reduced stabilizing effect. Summarizing the last two studies, they showed rather contradictory results concerning the effect of a LT during tendon/ muscle vibration. Nevertheless, we underline that haptic cues, provided during perturbed upright standing, appear to change the contribution of sensory cues to postural control in favor of proprioceptive and cutaneous cues.

Still, the following question remains to be explored. Does the effect of a LT during postural control of (quiet or perturbed) upright standing also apply to postural control during locomotion? This issue is of interest, if one considers that the study of haptic supplementation from a mobile support during postural control of upright standing is a preliminary step before studying its effect during locomotion.

1.2.5.2. Light touch during locomotion

Only two studies investigated the effect of a LT on a fixed rail during walking on a treadmill. They belong to the type of studies in which only task-inherent constraints were manipulated (haptic cues provided during complex postural tasks). Dickstein and Laufer (2004) showed a stabilizing effect of a LT (< 2 N) on a fixed rail on locomotor performance of young adults (which caused a decrease in COM variance). Fung and Perez (2011) observed similar results when testing older adults and older chronic stroke patients in a similar experimental setup. Specifically, Fung and Perez (2011) showed decreased stride duration variability, decreased COM excursions and increased gait speed through a LT (< 4 N) on a fixed rail. Both groups of researchers concluded that haptic cues serve as a sensory anchor for the spatial orientation of the body to the environment and earth vertical and, thereby, improve locomotor performance. However, Dickstein and Laufer (2004) emphasized the difficulty of generalization (from treadmill walking with a fixed rail) to walking over ground with a cane.

In summary, there is growing evidence supporting the functional benefit gained by a LT during complex postural tasks, such as rocker-board stance or even locomotion. Nevertheless, none of the presented studies used a mobile stick that could move with the oscillating body and that stayed in contact with the environment to provide sway-related haptic cues (see [Boonsinsukh et al., 2009], for an exception). Consequently, the combination of 1) a LT on a mobile stick and 2) a passive stimulus provided by the sway-related movements of the stick on the ground has never been tested in the literature before, neither during quiet nor during more complex balancing tasks. In the present work, first of all, we aimed to increase the mobility of the light-touch support and test its potential stabilizing effect. Subsequently, we aimed to study the effect of this kind of haptic cues in more complex postural tasks. This mobile-stick experimental strategy is a necessary step to explore the effect of a light touch on a mobile support before testing its effect during locomotion. Finally, though it was not the objective of the present thesis, our work could contribute to design a prototype of a portable haptic assistive device.

In line with Newell (1986)'s model, we present the different constraints that have been manipulated in the present work. First of all, by manipulating the sensory modalities (haptic or vision), the light-touch support (fixed or mobile) and the resistance to body sway (rough or slippery surface underneath the mobile support), we controlled the environmental constraints and, thereby, the types of sensory information available to the CNS. Moreover, by controlling the task-inherent constraints, we studied the effect of a LT on a mobile stick providing sway-related haptic cues in different postural situations (static vs dynamic and sitting vs standing). We also manipulated subject-related constraints, that is to say, we chose different groups of participants (young and older) for our experiments. Thus, before presenting the experimental paradigm adopted in the present work (chapter 2.) we will introduce age-related alterations within the NMSS and possible consequences of aging on postural control.

1.3. Age-related changes in postural control

Aging is characterized by (more or less) progressive alterations of various structures and functions of the NMSS, for example, cognitive [Zec, 1995], neuromuscular (sarcopenia; [Jang and Van Remmen, 2011]) or sensory alterations [Goble et al., 2009, Sturnieks et al., 2008]. It is recognized that corresponding functional declines, such as slower processing speed or impaired executive functions, muscle weakness or reduced sensory sensitivity have tremendous consequences on postural control of older adults and increase the risk of falls [Sturnieks et al., 2008]. Due to the complexity of the interactions between influencing factors, research on postural control and fall risk in older adults is challenging and, for example, the most effective fall risk prevention programs have been identified to follow multifactorial approaches [Lord et al., 2007, Tinetti et al., 1994].

However, in the present work, we chose to tackle the issue of age-related changes in postural control only via the study of its sensory components. Specifically, we studied sensory integration of healthy active older adults above the age of 65 years by the means of haptic supplementation. Consequently, we strictly defined the inclusion criteria for the groups of older adults that participated in our experiments. To be precise, we excluded adults with established sensory, motor and cognitive deficits and, thus, chose healthy active older adults. In the following, we present age-related changes of postural stability and the different sensory systems involved in postural control that could potentially be compensated by means of haptic supplementation.

1.3.1. Changes in postural stability with age

As previously mentioned, the COP trajectory is commonly used to assess postural stability. In addition, this stability measure captures the effect of normal aging. As the COP is currently admitted to continuously oscillate around the COM to maintain stable upright stance [Winter, 1995], the smaller the COP displacements the better postural stability is preserved and the more efficient is the regulation of the COM excursions [Horak, 2006]. This means, on the other hand, the larger, the more variable or rapid the COP displacements the less stable the balancing system and, accordingly, the less efficient postural control. Indeed, older adults have been repeatedly found to have larger postural sway during upright standing when compared to younger adults [Baccini et al., 2007, Horak, 2006, Maki et al., 1994, Menz et al., 2006] and to perform oscillations with higher COP velocity [Demura et al., 2008, Du Pasquier et al., 2003].

However, postural stability of healthy older adults during unstable sitting has been scarcely explored as the corresponding works focused on sitting postural deficits of very specific groups of participants that is, (older) patients with low back pain [Radebold et al., 2001, Van Daele et al., 2009, van Dieën et al., 2010] or stroke [Genthon et al., 2007, Perlmutter et al., 2010]. Yet, due to common principles of the postural control models for both sitting and standing, one can hypothesize that the COP trajectory captures the effect of normal aging during sitting as well.

In the frequency domain, age-related changes in postural control mechanisms were associated with two kinds of postural changes during upright standing. As mentioned above, some studies showed that older participants swayed more than younger participants [Baccini et al., 2007, Horak, 2006, Maki et al., 1994, Menz et al., 2006], whereas others showed smaller COP amplitude and higher MPF of the body sway [Carpenter et al., 2006, Vieira et al., 2009]. Higher frequency components were attributed to increased muscle activity and ankle stiffness. Moreover, higher MTP of the frequency spectrum of body sway has been currently observed in older adults [McClenaghan et al., 1996, Demura et al., 2008].

By means of the SDA, Collins et al. (1995) observed age-related changes in postural control mechanisms during upright standing. The authors showed that the transition between open-loop and closed-loop mechanisms took place at longer critical time intervals and larger critical mean squared displacement when compared to young adults. These results were interpreted as a sign for an age-related increase in postural instability as feedback-based control mechanisms only play a role in postural control after longer time delays. According to the authors, higher age-related values of the short-term diffusion coefficient refer to higher open-loop stochastic activity and may be explained by higher steady-state postural muscle activation predominantly used to control and stiffen a rather unstable system during open-loop control (see above, for a consistent stiffness-interpretation concerning the MPF). In the following, we present the contribution of age-related alterations of the different sensory systems to the postural instability of older adults.

1.3.2. Aging and sensory systems

Age-related sensory impairments occur as a result of alterations of the peripheral and central nervous system. In the following, we present the influence of age on the different sensory systems involved in postural control.

The visual system provides the CNS with a reference for verticality and for self-motion. Accordingly, age-related functional declines in distant contrast sensitivity and depth perception have been found to be independent predictors of increased instability in older adults [Lord and Menz, 2000]. The vestibular system provides the CNS with a gravito-inertial reference. Age-related impairments of the vestibular system lead to perceptive (vertigo or spatial disorientation) and oculomotor deficits (nystagmus or strabismus) and to impairments in posture and gait. These postural impairments occur especially when performing turns or head movements while walking or while upright standing on a rotating support surface. Accordingly, decline of vestibular function has been associated to postural instability and a higher risk of falls [Baloh et al., 2001]. Proprioception and force-related information from cutaneous mechanoreceptors ("somatosensory graviception") provide the CNS with a reference for the quality of the support surface, its texture and gravity. Age-related decline in joint position sense of the knee have been observed [Skinner et al., 1984], as well as decreased plantar tactile sensitivity [Perry, 2006], which have been associated with increased postural instability [Menz et al., 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 older adults [Lord et al., 1992]. In the context of the present work about haptic supplementation, it is noteworthy to introduce findings by Tremblay et al. (2005) on the loss of cutaneous sensitivity at the fingertips of older adults. Even though, in this study, no pathological changes have been observed by means of a gap-detection test at the fingertips, elderly showed half as much spatial acuity (~1 mm) when compared to young participants (~2.5 mm). Despite this difference in spatial acuity, elderly benefited to the same extent than young controls from haptic supplementation via a LT [Tremblay et al., 2004]. These two companion papers suggested that even with sensory impairments of the same sensory modality that is implied in a LT, the capacity to increase the weight of haptic cues to facilitate sensory integration is preserved with higher age (chapter 1.3.3.).

As 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 et al., 1991, Horak, 2006], the issue of central integration processes of older adults deserves to be addressed. If mechanisms of sensory reweighting cannot fully compensate for distorted or missing sensory information, these age-related alterations can lead to modifications of sensorimotor processes and, accordingly, to deficits in the adaptability of the postural control system [Spirduso et al., 2005]. As mentioned above, this manifests in postural instability of older adults in everyday life [Maki et al., 1994, Horak, 2006, Baccini et al., 2007]. Studies that were interested in the question whether older adults can compensate for external sensory perturbations showed contradictory results depending on the perturbing sensory stimuli (sinusoidal or discrete), some confirmed the capacity of sensory reweighting at higher age [Allison et al., 2006] and some did not [Horak et al., 1989, Teasdale et al., 1991]. We address this issue in further detail in the following section.

1.3.3. Sensory integration/ reweighting with age

The ability to flexibly adapt motor commands by multisensory integration and sensory reweighting in order to preserve balance in various and changing environmental conditions is considered one of the most critical factors for postural control in older populations (e.g., [Horak et al., 1989]). Sensory reweighting has been found to decrease with higher age [Teasdale et al., 1991]. This means that central mechanisms such as selection, processing and integration of multiple sensory cues work slower and/ or less accurately with higher age. However, Allison et al. (2006)'s result suggested that, even at higher age, the plasticity of sensorimotor processes and especially of multisensory integration is fully preserved. The authors compared young, older and age-matched fall-prone participants in the above-mentioned “moving-room” paradigm (chapter 1.1.5.4.). The used “gentle” sinusoidal sensory perturbation for a relatively long time period (120 sec) contrasted with previous studies that used severely changing sensory conditions. During these severe perturbations older adults achieved deficient central integration [Horak et al., 1989, Teasdale et al., 1991], such as slow sensory processing rather than deficient sensory reweighting itself [Woollacott et al., 1986]. In this situation of gentle sensory perturbation, results observed by Allison et al. (2006) suggested that intra- and inter-sensory reweighting occurred even in older fall-prone participants (with normal peripheral sensation). However, the influence of age on the time scales of sensory reweighting remains unclear.

The issue of compensation between sensory sources is of particular importance in the context of haptic supplementation. Indeed, if the capacity to compensate is altered, one can predict that the benefits of haptic supplementation will be limited or absent. Otherwise, compensation between different sensory modalities and, thus, compensation of age-related sensory loss by haptic supplementation should occur.

At this point, we introduce the notion of “non-specificity” of haptic cues perceived at the fingertip in the context of postural control. Indeed, in contrast to cutaneous and proprioceptive cues from the feet that provide a reference for somatosensory graviception during upright standing, haptic information from the fingertips are not generally used to control posture. However, these cues can be detected, processed and presumably efficiently used by the CNS to improve postural control. As presented in the general introduction, LT of a wall or a partner’s arm during locomotion can be observed in everyday life suggesting that haptic cues are naturally used in specific situations to enhance postural stability. As mentioned above, “posture-specific” visual, vestibular and proprioceptive cues are altered with higher age. In the present work, we were interested in whether “non-posture-specific” haptic cues from the fingertips could compensate for age-related sensory impairments of “posture-specific” sensory cues.

Evidence for the capacity of dynamic sensory reweighting with higher age has been provided by studies showing the stabilizing effect of haptic supplementation in older adults during upright standing [Baccini et al., 2007, Reginella et al., 1999, Rogers et al., 2001]. Some authors even found that older adults benefited more than young adults from a LT or PS [Baccini et al., 2007, Rogers et al., 2001]. Further evidence comes from studies about the effect of sensory enhancement on postural stability in older adults. Gravelle et al. (2002, Figure 9 left, see also [Priplata et al., 2003]) observed a stabilizing effect through the application of low-level electrical noise to the subject's skin (here: to the knee) during unipodal upright stance. The results suggested that this technique enhances the proprioceptive sensitivity, overcomes increased sensory thresholds with higher age and enhances the sensory cues available to the CNS. This work underlines the efficient sensory reweighting mechanisms of older adults.

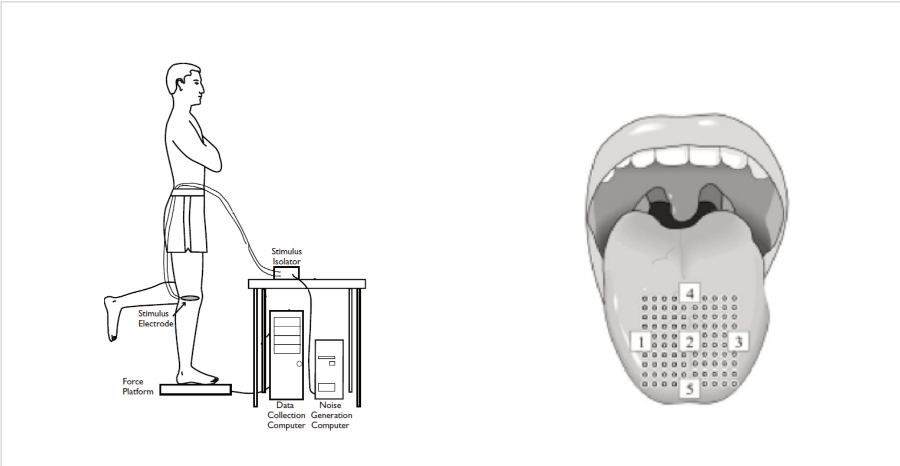

Figure 9: Experimental setup for sensory enhancement (on the left) and sensory coding scheme of a electrotactile device (on the right): stimulation as a function of the head orientation relative to gravity: 1) right bended, 2) neutral, 3) left bended, 4) extended and 5) flexed
Adapted from [Gravelle et al., 2002] (on the left) and [Danilov et al., 2007, Vuillerme et al., 2008] (on the right)

Similarly, biofeedback devices exist that are used in the rehabilitation of patients with balance dysfunctions to regain or increase postural stability (e.g., BrainPort Balance Device, Wicab Inc., Figure 9 right). The principle behind such devices is to substitute missing or inaccurate sensory information about the spatial orientation (due to peripheral or central impairments) by biofeedback about the head orientation via another sensory modality (i.e., vibration as a modality of cutaneous receptors on the tongue). After a period of familiarization, users can learn how to use the "non-posture-specific" electrotactile information from the tongue informing about head orientation in order to counteract postural deviations. Danilov et al. (2007) used this kind of electrotactile biofeedback in older adults with chronic balance dysfunction during upright standing and participants appeared to be more stable with the device than without. Haptic supplementation stands in contrast with this kind of electrotactile biofeedback, as its stabilizing effect has been shown to be instantaneous even without a period of familiarization or handling instructions. One could hypothesize that even after the period of familiarization, the use of electrotactile biofeedback necessitates higher attentional demands than the use of haptic cues. This could be due to the implication of a sensory modality (vibration on the tongue) that is completely new for the CNS in the context of postural control.

Two other interesting examples concerning “intra-modality” sensory reweighting of older adults have been given by Dickstein et al. (2001) and Tremblay et al. (2004, 2005). The latter authors suggested in the above-mentioned two companion papers that even with sensory impairments of the sensory modality implied during the LT (age-related decline in spatial acuity at the fingertips), the capacity to increase the weight of haptic cues to facilitate sensory integration and postural control is preserved with higher age [Tremblay et al., 2004, Tremblay et al., 2005]. Similarly, Dickstein et al. (2001) observed that neuropathy patients with chronic somatosensory loss in the feet could benefit more from a LT than healthy controls. These results suggested that, despite potential somatosensory impairments of the sensory modality implied during the LT, patients can use additional haptic cues from the fingertips, hand and arm to compensate for deficient foot-somatosensory information. That means that compensation occurs within the same sensory modality between sensory cues from two different locations (foot and fingertip).

1.3.3.1. Haptic supplementation in older adults

The potential benefit of haptic supplementation provided by a mobile stick for older (unstable) adults is of great interest as age-related alterations that affect postural control determine the degree of mobility, the risk of falling and, finally, the autonomy of older adults in daily living activities. Classically, reinforcement of postural control mechanisms, as part of a (fall) prevention strategy, includes specific training programs [Lord et al., 2007] and, in the most extreme cases, the prescription of walking aids to preserve postural stability ([Bateni and Maki, 2005], for review). 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" sensory assistance rather than from firm mechanical support. As mentioned above, Reginella et al. (1999) observed a stabilizing effect of a LT in older adults and, even more, Baccini et al. (2007) and Rogers et al. (2001) showed that older adults benefited even more than young people from a LT on a fixed support. On the basis of the existing literature on haptic supplementation and postural control, one can suggest that haptic supplementation from a cane could strengthen or assist postural control mechanisms and might be especially helpful to compensate for postural instability and enhance mobility in older adults or populations suffering from sensorimotor alterations of neural origin.

1.3.3.2. Haptic supplementation in older vestibular patients

Among the functional changes associated with aging, especially those affecting the vestibular system influence mechanisms of sensory integration and impair postural stability and locomotor performance during everyday life. Understanding how corresponding functional deficits may be diminished or compensated with the help of haptic supplementation is of importance in the field of aging research and associated pathologies. Age-related changes of the vestibular system can lead to impairments in posture and gait and such behavioral changes progressively degrade with age. Accordingly, decline of the vestibular function has been linked to a higher risk of falls [Baloh et al., 2001]. Indeed, Lackner et al. (1999) showed the stabilizing effect of a LT on a fixed support in patients with bilateral loss of vestibular function during quiet upright standing. In a similar way, a stabilizing effect through the use of electrotactile biofeedback was found in older patients with bilateral vestibular loss by Barros et al. (2010). Results suggested that, externally sensed information about the head orientation that is translated into a "non-posture-specific" modality (vibration as a modality of cutaneous receptors) can be used by the CNS of vestibular patients to improve postural stability. Thus, one can hypothesize that haptic supplementation provided at the hand via a light touch of a mobile support (cane) could improve postural stability and locomotor performance in older adults with vestibular disorders.

A specific surgical treatment for a group of patients suffering from severe vertigo - so-called vestibular neurotomy - is frequently used to improve the quality of life of patients. It consists of a division of the vestibular nerve in order to suppress perturbing vestibular cues. After surgery, patients go through a period of adaptation to the systemic changes usually with a compensation for the missing sensory input after a period of some weeks or months. In a first period after surgery, patients experience some days of being bedridden with perturbed postural control. Later on, they learn to regain postural stability and locomotor performance during rehabilitation. One can hypothesize that haptic supplementation could improve postural stability of patients who underwent vestibular neurotomy during rehabilitation. A more pronounced stabilizing effect for vestibular neurotomy patients after compensation would be expected, as the compensation usually occurs in favor of proprioceptive cues, which might facilitate the use of haptic information for postural stabilization. Research in this field is of fundamental interest as the postural control system after neurotomy is a suitable system for understanding the role of neuro-plasticity in postural control. Secondly, it is of clinical interest considering patient-centered care and patient's comfort. These issues have been addressed during the PhD thesis in a collaborative program carried out with clinicians specialized in the vestibular system (chapter 9.).

1.4. Objectives of the present work

Through this literature review, we have shown that evidence exists supporting the benefit of a LT on fixed or (more or less) mobile supports to provide additional spatial orientation cues in both static and more complex dynamic postural tasks. Results observed in studies using the passive-stimulus paradigm suggested that changes in cutaneous information related to body oscillations from an externally applied passive "scratch" is functional for postural stabilization. Thus, the question arises of whether this type of sway-related information can be mediated by a mobile stick that is free to move with the oscillating body. This question is of theoretical interest and, at the same time, potentially important for the design of a portable assistive haptic device.

To our knowledge, few studies if any have used a LT in a mobile-stick experimental paradigm, where the support could move with the oscillating body to provide sway-related haptic cues through the interaction with the environment. Specifically, the combination of a LT on a mobile support with a PS provided by the sway-related movements of the support on the ground has never been tested in the literature. Yet, exploring the effects of sway-related haptic supplementation using a mobile stick (that is, presumably in absence of a fixed reference point) appeared to be a crucial step for understanding whether additional haptic cues could be provided by portable assistive devices in everyday life of older (unstable) adults.

Accordingly, the general objective of the present work was to investigate the effect of sway-related haptic cues provided by a mobile support on postural stability in both young and older people in different postural tasks. Based on Newell (1986)'s model, the different experiments aimed at better understanding whether and how different 1) environmental, 2) task-inherent and 3) subject-related constraints influenced postural control and postural stability. This has been done by using different strategies throughout the experimental program.

The first general objective was to better understand multisensory integration that is, to determine whether and how the CNS can make use of haptic cues in order to improve postural control. In this aim, we controlled the types of sensory information available to the CNS to study their impact on postural control. Specifically, we manipulated the sensory modalities ("non-posture-specific" haptic vs. "posture-specific" visual cues), the stability of the light touch support (fixed vs. mobile) and the resistance offered by the support against body sway (rough vs. slippery surface).

Another general objective was to determine if haptic cues can be effectively integrated for postural stabilization in different postural situations. For this purpose, we also manipulated 1) the complexity of postural tasks (static vs. dynamic situations) and 2) the biomechanical system involved in the task (sitting vs. standing).

In addition, we aimed to determine whether older adults can effectively make use of haptic cues to improve postural stability knowing about potential changes in sensory systems and sensory integration with higher age. Specifically, we compared different age groups, while controlling for the functional status of different postural control systems (healthy older adults), and studied how they benefit from haptic supplementation.

Finally, the present work represents a preliminary step to better understand what kind of information is used by the CNS to better control posture, and then to clear the way for future research about a portable haptic assistive device during locomotion.

In the second part of this manuscript, we will introduce the experimental paradigm chosen to implement the above-mentioned objectives. Subsequent to this (chapters 3. to 7.), we present the five different studies and the different specific hypotheses when introducing each study.

2. Experimental strategy

2.1. Light-grip paradigm

The reviewed literature suggested that three different types of haptic feedback might be used to improve postural control [Krishnamoorthy et al., 2002, Slijper and Latash, 2000]. On the one hand, we described a procedure of haptic supplementation that allows providing a fixed light-touch support that acts as a spatial referent and that presumably gives rise to an accurate representation of the body orientation (e.g., [Holden et al., 1994, Jeka and Lackner, 1994, Jeka and Lackner, 1995, Reginella et al., 1999]). On the other hand, we described a procedure that allows providing sway-related cutaneous and proprioceptive information at the fingertip due to the use of a mobile light-touch support. These cues presumably help estimating self-motion even in the absence of a spatial referent [Krishnamoorthy et al., 2002, Lackner et al., 2001]. Another third procedure (PS) allows creating shear forces at the skin by externally applying a stationary rough surface [Rogers et al., 2001, Menz et al., 2006]. These shear forces are related to the body sway and presumably enhance self-motion perception. All three procedures have been found to improve postural stability. In contrast to the first one, the latter two underline the importance of sway-related changes in contact forces (and proprioception) for postural stabilization.

In the present work, we introduced a mobile-stick experimental paradigm that combined a LT on a mobile support with a PS. More precisely, this new paradigm was designed to transpose the passive “scratch” stimulus (from the skin as observed during a PS) to the end of the lightly-gripped mobile support. In the same way that we perceive, for example, the texture of a paper via the mediation of a pen during writing [O’Regan and Noë, 2001] we expected participants to perceive sway-related feedback through the slight movements of the mobile support on a stationary surface. This kind of combination has not been tested in the literature but appeared to be a crucial step towards a mobile “cane-like” support that could be of potential benefit during locomotion in everyday life. In contrast to the LT of only the index finger known in the literature, the mobile support (stick or pen) in the present work was to be held with a light grip (LG) of three fingers (index, thumb and middle finger). This is why the paradigm presented here can also be called “light-grip paradigm”.

We hypothesized that this kind of sway-related feedback from the interaction of the mobile support with the environment would enhance self-motion perception and improve postural stability even in the absence of a spatial referent. We further hypothesized that it would become perceivable given that sufficient resistance was offered by the mobile support against body oscillations. In order to test these hypotheses, we designed the mobile-stick experimental paradigm to compare the effect of a LG of fixed or mobile supports. Furthermore, we manipulated, in the mobile-support conditions, the different surfaces provided underneath the extremity of the mobile support. In the following, we describe the common principles of the experimental conditions in the different experiments.

2.2. Task and experimental design

Depending on the study design, the participants were tested in a standing (studies I, II, IV and V) or a sitting task (study III) with or without haptic supplementation. A force platform was used to record the resultant ground reaction force to determine the COP trajectories.

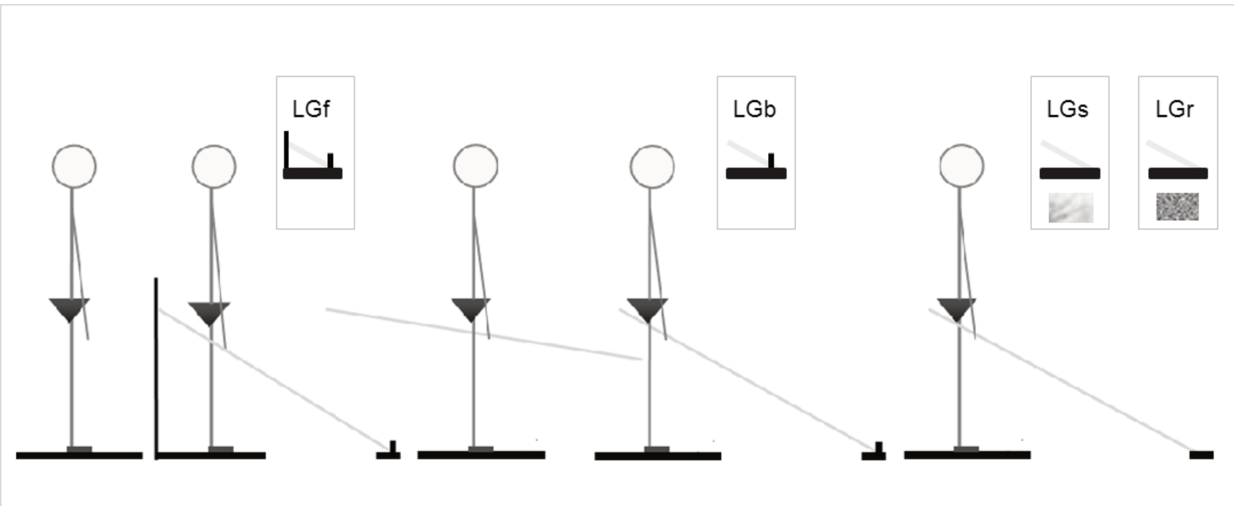

Figure 10: Six experimental conditions of studies I and II (see Figure 12 left, for grip details)

Haptic supplementation was provided by a LG of a fixed or mobile support. During standing, the light-grip support was a stick that was inclined to the ground in front of the participants (Figure 10, chapter 2.4.1.). During sitting, the light-grip support was a pen that was inclined to an elevated table next to the participants (Figure 11, chapter 2.4.2.).

At the beginning of each experiment, participants had a period of 3-5 min of familiarization with the task. During this period, participants learned to conform to the grip instruction that is, to perform a LG not exceeding a force threshold (< 1.2 N during sitting and < 1.6 N during standing).

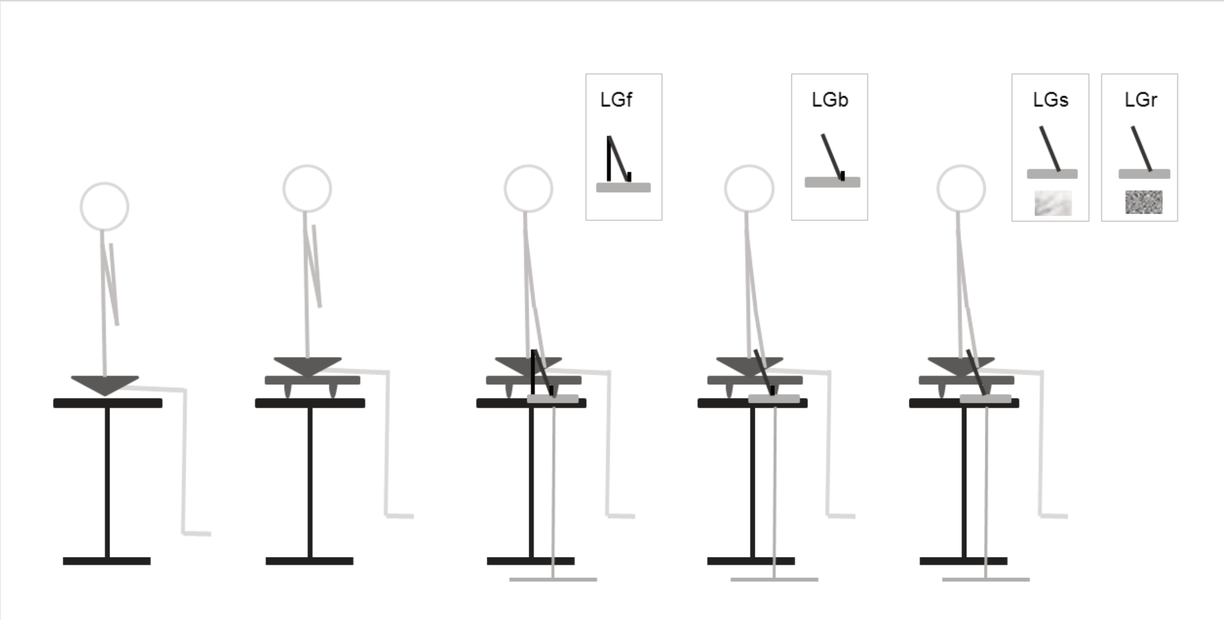

Figure 11: Six experimental conditions of study III (see Figure 12 right, for grip details)

This threshold corresponded to the classical force threshold during LT in the literature of around 1 N. Herewith, the possibility of a mechanical aid by the support was excluded [Holden et al., 1994].

In all conditions, participants were asked to hold the arm involved in the LG straight along the side of the body and to focus their attention on the postural task (not on the LG). In order to test the effect of a LG of fixed or mobile supports on postural stability, the mobility of the support and its resistance against body oscillations were manipulated in the different experimental conditions.

2.3. Experimental conditions

In all experiments of the present work, six experimental conditions were run in a randomized order across participants (except study V with only five conditions that is, without a quiet balance condition):

1) A quiet-balance condition used as a reference condition (QS, 'quiet stance' or 'quiet sitting')
2) A fixed-support condition (LGf, 'light grip fixed'), in which participants lightly gripped the support that was fixed in space. Its rear extremity was attached to a structure and its front extremity was immobilized on a stationary surface. This condition presumably furnished haptic cues and a spatial referent in both the plane of greatest instability (e.g., AP direction during standing) and in the plane orthogonal to it (e.g., ML direction during standing). It was similar to a classical LT on a fixed support [Jeka and Lackner, 1994, Holden et al., 1994]. Results of a pilot experiment confirmed that the same stabilizing effect was obtained by a LT or a LG on a fixed support.
3) A blocked-support condition (LGb, 'light grip blocked'), in which participants lightly gripped the support that was mobile at its rear extremity, while its front extremity was blocked on a stationary surface. This condition presumably furnished sensory cues in the plane of greatest instability (e.g. AP, direction during standing) but not in the plane orthogonal to it (e.g., ML direction during standing). It provided a spatial referent in form of the stationary surface at the front extremity of the support which was mediated by a mobile support. It was similar to the slanted-cane condition tested by Jeka et al. (1996), as the inclined mobile support pivoted around a stable point.
4) A slippery-surface condition (LGs, 'light grip slippery'), in which participants lightly gripped the support that was free to move on a slippery surface.
5) A rough-surface condition (LGr, 'light grip rough'), in which participants lightly gripped the support that was free to move on a rough surface. In these latter two conditions, both the rear and the front extremity of the support were entirely mobile. These conditions combined a LT and a PS, as the light-grip support could move with the oscillating body. These conditions presumably provided more (LGr) or less (LGs) easily detectable sway-related haptic cues in the plane of greatest instability (e.g., AP direction during standing) but not in the plane orthogonal to it (e.g., ML direction during standing). No spatial referent was provided in these conditions.

The sixth condition varied throughout the experiments and we will present details in the methods section of each corresponding experiment.

2.4. Apparatus

The type of force platform, motion analysis system and rocker board used in the different experiments are presented in the methods section of each of the corresponding experiments.

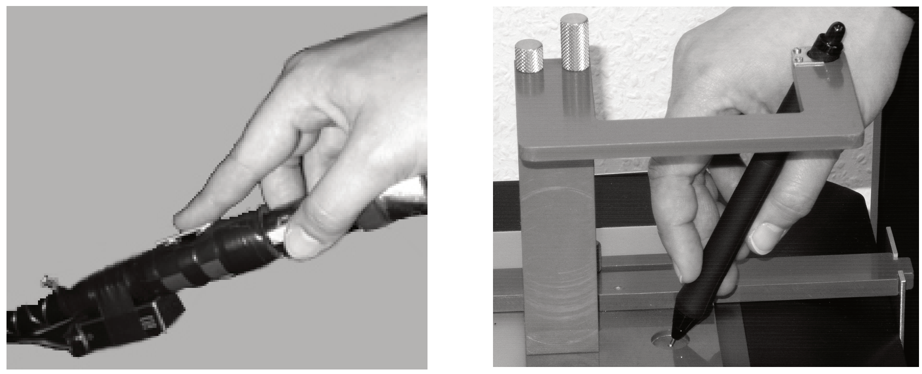

Figure 12: LG of the instrumented stick (on the left) and the digitizer pen in the LGf condition (on the right)

2.4.1. Stick support

Haptic supplementation was provided by the LG of a stick in the standing experiments (study I, II, IV and V, Figure 12 left). The handle at the rear extremity of the stick (weight: 400 g, length: 165 cm) was instrumented with six micro switches – each 2 switches were covered by a badge of steel (2.5 cm). Two switches were dedicated to the index finger on top of the stick handle (53 cm away from the rear extremity). Four others were dedicated two to the thumb and two to the middle finger on both lateral sides (47.5 cm away from the rear extremity). Each of the switches released and lightened a LED when the force exerted by the corresponding finger exceeded 1.6 N. If this was the case during the experiment, the trial was rejected and repeated.

In a pilot experiment, we examined the global amount of forces applied by the stick extremity on the ground in case of release of the micro switches. A Nano25 transducer (ATI, Industrial automation, Inc., NC, USA) was used that converted force and torque into analog strain gauge signals. Results confirmed that, in case the switches released (rejected trial) the applied force by the front extremity of the stick did not exceed 2.5 N. This further excluded any mechanical aid by the stick [Holden et al., 1994]. The position and height of the stick were both adjustable due to an adjustable metal structure, used to fix the stick at its rear extremity (in the LGf condition), while keeping a steady angle of 30° relative to the ground in all conditions of haptic supplementation. In the LGr and LGs conditions, the difference in texture between the slippery (plastic) and the rough surface (sandpaper: 120 granulation) corresponded to dynamic frictional coefficients of 0.37 and 0.58, respectively.

2.4.2. Pen support

Haptic supplementation was provided by the LG of a pen in the sitting experiment (study III, Figure 12 right). This pressure-sensitive electromagnetic resonance pen of a digitizer tablet (Intuos4, Wacom Company Ltd.) served to digitize the applied forces in the conditions of haptic supplementation (LGf, LGb, LGr and LGs) and the pen displacement in the two mobile-support conditions (LGr and LGs). The digitizer was positioned on an adjustable table on the right side of the participants at around hip height. The pen (weight: 17 g, length: 15.3 cm plus 6 mm of metallic lead) and digitizer were connected to a PC indicating by an acoustic signal when applied forces exceeded 1.2 N (1 N plus the weight of the pen). If this was the case during the experiment, the trial was rejected and repeated. The position and height of the pen support were adjustable, while keeping a steady angle relative to the digitizer. In the LGb condition, only the front extremity of the pen was blocked in a drilled hole of a stationary plastic attachment mounted to the digitizer. The drilled hole in the attachment blocked the pen, while ensuring a constant contact with the digitizer. In the LGf condition, also its rear extremity was attached to the same attachment (Figure 12 right). In the conditions LGr and LGs, different textures were used in the slippery- (unruffled plastic) and the rough-surface condition (textured plastic, d-c-fix® Milky Glass Decorative Static Cling Film).

3. Study I: Haptic supplementation provided by a fixed or mobile support

3.1. Introduction

The general objective of this experiment was to better understand whether and how the CNS of healthy young participants can make use of haptic cues provided by the LG of a fixed or mobile stick in order to improve postural control during upright standing. To this end, we controlled in the present experiment the types of sensory information available to the CNS in order to study their impact on postural control. Thus, according to Newell (1986)'s model, we manipulated only the environmental (sensory cues) factors of postural control, while choosing a simple quiet-stance task and testing only young participants. Specifically, we manipulated the stability of the light-grip support (fixed vs. mobile) and the resistance offered by the support against body sway (rough vs. slippery surface).

The adopted mobile-stick or light-grip paradigm differed from previous light-touch studies in the literature with respect to at least three important aspects. 1) The LG with three fingers permitting to hold a mobile stick, which is of importance in view of potential applications, such as a portable haptic assistive device, that could be used during locomotion. 2) The handle and the extremity of the stick were either fixed or mobile in both the AP and ML directions, presumably testing the effect of haptic cues from the LG of a stick in presence or in absence of a fixed reference point in the environment. 3) In the mobile-support conditions, the extremity of the stick was free to move on a slippery or a rough surface, testing the role of more or less resistance provided against body oscillations that presumably leads to more or less easily detectable sway-related haptic feedback.

As mentioned above, in a pilot experiment, we have verified that the LT and the LG on a fixed support resulted in equivalent postural stabilization.

3.2. Aims and hypotheses

We predicted that the stabilizing effect of a LG on a fixed or mobile stick is independent of the nature of the support. This hypothesis has theoretical implications. It means that postural stabilization should depend on the availability of sway-related changes in cutaneous and proprioceptive cues informing the participants about their body oscillations and not on the availability of a spatial referent. Accordingly, we hypothesized that sway-related haptic cues from a mobile stick improve postural stability even in absence of a fixed reference point. We further hypothesized that more resistance is provided by the stick movements on a rough surface than on a slippery one. This should result in less easily detectable sway-related haptic cues from the interaction with the slippery surface and in a less stabilizing effect of this kind of haptic cues (when compared to the rough-surface condition).

3.3. Materials and methods

3.3.1. Participants

Eleven young participants (7 females and 4 males, mean age 25.9 years ± 1.9 years) took voluntarily part in the experiment. They were right-handed, physically active and had no self-declared musculoskeletal injuries, or perceptive, cognitive and motor disorders that might affect their ability to maintain balance or to understand task instructions. The experimental protocol was presented to all participants, which gave a written consent before undergoing the experiment. The protocol was approved by a local ethics committee and has therefore been in accordance with the ethical standards laid down in the declaration of Helsinki.

3.3.2. Task and experimental design

The participants stood on a force platform with eyes open (EO) in conditions with or without haptic supplementation. The feet of the participants were placed at hip-width, side-by-side and the toeholds were positioned in a distance of 20 cm, in an angle of 30°. Participants were instructed to adopt a natural standing position and to maintain this position as stable as possible, while fixing a point placed in eye height at 1.5 m on a wall. Adhesive tape was used to mark participant's position on the force platform so that the same task configuration was repeated each trial. By means of an adjustable Velcro®- bandage, both arms of participants were kept straight along the body in all conditions. Constant distance between the arms and the body was maintained by two foam pads (12 cm x 8 cm x 1 cm). Haptic supplementation was provided through the LG of a stick with the right hand (chapter 2.4.1.). Six experimental conditions were tested (Figure 10): 1) quiet stance (QS), 2) a fixed- (LGf), 3) a horizontal- (LGh), 4) a blocked-support condition (LGb), 5) a slippery- (LGs) and 6) a rough-surface condition (LGr). In the five conditions of haptic supplementation (LGf, LGh, LGb, LGs and

LGr), the mobility of the stick and its resistance to body oscillations were manipulated. In the horizontal-support condition (LGh, 'light grip horizontal') participants lightly gripped the stick at its longitudinal center and held it in a roughly horizontal position. This condition was similar to the horizontal-cane condition tested by Hausbeck et al. (2009) and was designed to test if only the LG of an object (light-grip support of a certain weight) enhanced postural stability. As the stick was not in contact with the environment, this condition presumably provided minimal transient sway-related inertial forces created by the hand-held stick. It represented a control condition within the conditions of haptic supplementation. Participants did three trials of 30 s in each condition. Breaks lasted 30 s between each trial and 60 s between each condition. The total experimental session lasted about 1 hour.

3.3.3. Apparatus and measures

The force platform (AMTI, Advanced Mechanical Technology, Inc., MA, USA) measured the three components of the resultant ground reaction force to determine the COP trajectories in the AP and ML directions. The sampling rate was set to 200 Hz. Data were collected by means of LabView 7.5 (National Instruments®, Austin, TX, USA) on a PC and analyzed offline with the help of Matlab 7.0 (The MathWork®, Inc., Natrick, MA, USA). Based on COP trajectories, three dependent variables were calculated for each trial: 1) the RMS [mm], 2) the range [mm] and 3) the MV [mm/s] (see chapter 1.1.2.).

The individual data obtained for each trial in each condition were averaged and used to carry out 6-conditions repeated-measure ANOVAs. Normality was checked by means of Kolmogorov-Smirnov tests. Moreover, we calculated the percentage decrease of the range in the different conditions that showed a significant stabilizing effect relative to the QS condition (LGf, LGb and LGr). Mean percentages of stabilization obtained as the result of QS-LGf, QS-LGb and QS-LGr differences were submitted to an Arcsine transformation [Abdi, 1987] and then compared using 3-conditions repeated-measure ANOVAs. Significant effects were further analyzed using Newman-Keuls post-hoc tests (threshold of significance at $P<0.05$).

3.4. Results

In the following the effects of fixed- or mobile-support conditions in the most unstable plane (AP direction) and in the most stable plane (ML direction) are described. Even though the results of the post-hoc tests are not reported in detail, the differences between experimental conditions presented in the following were all significant or showed a trend (P=0.06).

3.4.1. Effect of fixed- or mobile-support conditions in the antero-posterior direction

The analysis of the RMS revealed an effect of condition ($F(5,50)=6.88$, $P<0.05$). The post-hoc decomposition showed that the RMS observed in the conditions QS, LGh and LGs did not differ significantly (Figure 13). In contrast, the RMS observed in the conditions QS, LGh and LGs was higher than in the conditions LGf, LGb and LGr (Figure 13). In contrast, the analysis did not reveal significant differences between the conditions LGf, LGb and LGr.

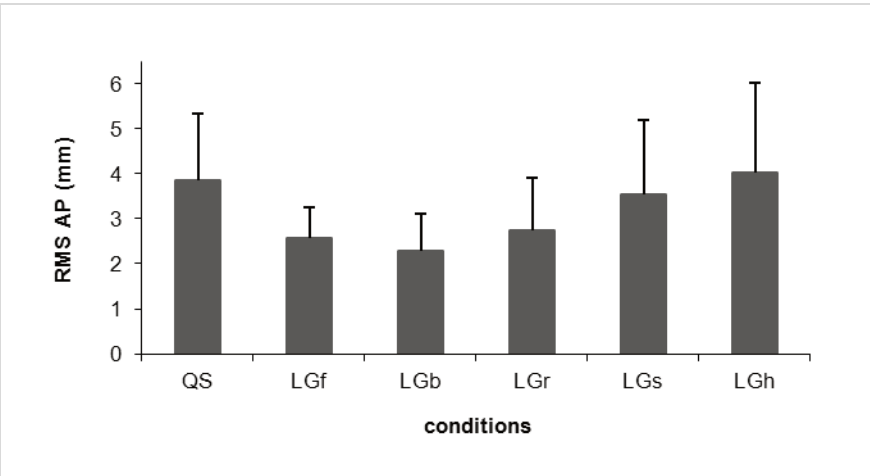

Figure 13: RMS of the COP (means and standard deviation) in the AP direction that is, in the most unstable plane

Similarly, the analysis of the range of the COP revealed an effect of condition ($F(5,50)=9.23$, $P<0.05$). The post-hoc decomposition showed that the range did not differ significantly between the conditions QS (18.6 mm), LGh (19.6 mm) and LGs (17.7 mm). On the other hand, the range was higher in these conditions (QS, LGh and LGs) than in the conditions LGf (13.4 mm), LGb (12.8 mm) and LGr (13.8 mm), which did not differ significantly from each other. The analysis of the percentage decrease of the range did not reveal an effect of condition (*F*(2,20)=0.66, *P*>0.05). Thus, the percentage decrease observed in the conditions LGf (24%), LGb (30%) and LGr (25%) did not differ significantly from each other.

3.4.2. Effect of fixed- or mobile-support conditions in the medio-lateral direction

The analysis of the RMS did not reveal an effect of condition (*F*(5,50)=1.61, *P*>0.05). Even though failing significance (*P*=0.08), the RMS variability in the LGf condition appeared to be smaller than in the QS condition (Figure 14).

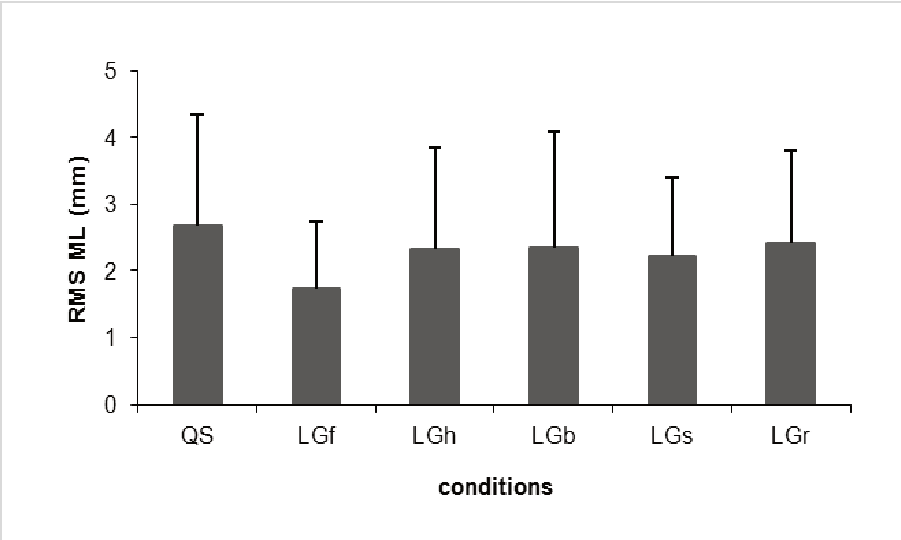

Figure 14: RMS of the COP (means and standard deviation) in the ML direction that is, in the most stable plane

The analysis of the range revealed an effect of condition (*F*(5,50)=2.60, *P*<0.05). The post-hoc decomposition showed that the range observed in the condition QS (13.8 mm) was larger than in the LGf condition (9.6 mm). The conditions QS, LGh, LGb, LGs and LGr did not differ significantly from each other. The analysis of the percentage decrease of the range did not reveal an effect of condition (*F*(2,20)=2.70, *P*>0.05). The percentage decrease observed in the conditions LGf (27%), LGb (0.1%) and LGr (0%) did not differ significantly from each other. The analysis of the MV did not reveal an effect of condition in any of the two directions. Therefore, this variable will not be mentioned in the following.

3.5. Discussion

3.5.1. Effects of a light grip on postural stability

This experiment aimed to test the effect of different conditions of haptic supplementation provided by a LG of a fixed or mobile stick on postural stability of healthy young people during quiet upright stance. The results confirmed our main hypothesis that haptic supplementation independent of the nature of the support leads to postural stabilization given that detectable information about body oscillations is provided.

Before discussing the results observed in this respect, it should be noticed that postural stabilization was observed in both the AP and ML directions in the LGf condition relative to the QS condition. However, lower percentage decreases of the range (24% to 27%) were observed in this condition when compared to others currently observed in the light-touch literature (e.g., > 50%, [Jeka and Lackner, 1995]). An explanation of these discrepancies lies in the possible existence of a ceiling effect in the present experiment. Indeed, in Jeka and Lackner (1995)'s study, postural oscillations were experimentally increased by the use of a tandem-stance position and visual restriction. In contrast, in the present experiment, participants performed a more natural upright standing task with the feet side-by-side and EO. A second explanation, not exclusive to the previous one, lies in the fact that the touching arm was strapped to the body and consequently not orientated in the most unstable plane as in Jeka and Lackner (1995)'s study. This explanation is supported by Rabin et al. (1999)'s results which showed that this arm orientation led to larger changes in joint angles and fingertip forces. The link between the direction of postural oscillations and the provided sensory cues appeared to be stronger with this arm orientation. Finally, in the present experiment, both arms of the participants were strapped to the body. Accordingly, freezing the DoFs of the kinematic chain of the arm (i.e., elbow and shoulder) and, thus, restricting joint movements to the wrist and fingers, might have reduced available proprioceptive information. Hence, it could be speculated that postural corrections were less effective since less sensory information was available to detect body movements. Anyway, as observed by Rabin et al. (2008), even if proprioceptive cues arising from the arm involved in the LT were kept constant by immobilizing the arm of the participant, it appeared that information arising from changes in contact forces on the fingertips were sufficient to allow a significant decrease in postural oscillations.

3.5.2. Effects of fixed- and mobile-support conditions in antero-posterior direction

In the most unstable plane (AP direction), a decrease of the RMS and the range were observed in the three conditions LGf, LGb and LGr. Two other conditions (LGh and LGs) did not significantly stabilize posture. As, all conditions of haptic supplementation involved an equivalent supra-postural task of lightly gripping the stick, the effect of haptic supplementation cannot be interpreted as the result of goal-oriented postural organization toward the supra-postural task, in order to better achieve the light grip of the stick [Riley et al., 1999]. The differences in postural stability across conditions rather suggested that sway-related haptic cues provided in the three stabilizing conditions (LGf, LGb and LGr) can be used by the CNS to improve postural control. They further suggested that the haptic cues appear to be absent or not detectable in the other two conditions (LGh and LGs).

The present results do lend credence to our hypothesis about the benefit of haptic supplementation independent of the nature of the support (i.e., fixed or mobile). Indeed, among the stabilizing conditions, in one condition haptic cues were provided by the LG of a fixed support (LGf) and in the two others by a mobile support (LGb and LGr). These findings suggested that the three conditions of haptic supplementation share, at least in part, common characteristics with respect to haptic inputs provided to the participants for postural control. This interpretation is in agreement with Krishnamoorthy et al. (2002)'s results suggesting that the availability of a fixed reference point during a LT may not be necessary to reduce sway, if the modulations of contact forces at the fingertip 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 hypothesized that the three conditions (i.e., including those providing a mobile support) provide haptic cues, such as transient contact forces and proprioception related to body oscillations. Specifically, in the two mobile-support conditions, the stick encountered a resistance against the body sway either by blockade (LGb) or the rough surface (LGr). Since these situations produced a comparable stabilizing effect to the one produced by a fixed support, one can hypothesize that this resistance plays a prominent role in postural control by creating sway-related transient contact forces.

A striking result was that no significant difference was observed between the conditions LGb and LGr concerning the RMS and the range. In both conditions, the handle was free to move in the ML direction, whereas a further mobility in the AP direction was added in the LGr condition. We hypothesized that changes in contact forces, which result from the stick movements on the ground, provide postural stabilization. The present results confirmed this hypothesis. They extended thereby Jeka et al. (1996)'s findings about the stabilizing effect of a stick pivoting around a stable point on the ground. One could conclude that the functionality of sensory cues is not biased by the mediation of the stick as compared to a LT with the fingertip [Lackner et al., 2001]. This benefit was of the same magnitude than the one provided by a LG on a fixed support and was even more noteworthy as observed in young healthy participants in an unperturbed situation. These findings suggested that a stabilizing effect on posture can be gained, even in absence of a fixed reference point, under the condition that functional sway-related contact forces are provided [Krishnamoorthy et al., 2002]. As expected on the basis of the results of previous studies [Lackner et al., 2001, Rabin et al., 2008], the effects of haptic supplementation still persisted even when a relative movement between the stick and the ground was created (see [Rabin et al., 2008], for relative movement between the finger and the support). Thus, our mobile-stick experimental paradigm, that approached a natural situation of stick use, permitted to merge different aspects of haptic supplementation by a LT and a PS. Finally, our results confirmed the stabilizing effect of a LG of a mobile stick.

The results observed in the ML direction strongly supported the importance of sway-related contact forces on the fingertips for postural stabilization. Indeed, in the ML direction, no stabilization was observed in the mobile-support conditions (LGb and LGr). Presumably, this is due to the fact that no resistance was offered by the stick against postural oscillations due to the mobility of the stick handle. These results also suggested that body oscillations in the ML and AP directions are controlled separately as, in some of the mobile-support conditions (LGb and LGr), postural stabilization was observed in the AP direction but not in the ML direction.

The results observed in the LGh and LGs conditions also supported the above-mentioned interpretation. Indeed, no stabilization effect was observed in both the LGh and LGs conditions. According to the line of reasoning followed above, this suggested that both situations share comparable characteristics, namely the lack of additional detectable sway-related haptic information. Thus, the question remains of whether 1) additional haptic information were really lacking in both the LGh and LGs situations due to the nature of the support or whether 2) the quiet-stance task was not the appropriate situation to make sway-related information detectable or functional for participants in these conditions.

With respect to the LGh condition, the second hypothesis is supported by Hausbeck et al. (2009)'s findings. Hausbeck et al. (2009) did not observe a stabilizing effect of a horizontal-cane condition (similar to LGh) when vision was untroubled. However, when troubled, gripping the horizontal-cane led to postural stabilization. These results suggested that a more perturbing postural situation creates detectable transient inertial forces that were undetectable or not functional in the present study. From another point of view, one could suggest that the CNS relies more on information provided by small transient (inertial) contact forces in more demanding or sensory-conflicting situations. Such speculative hypothesis deserves however further investigation, for instance in the context of mechanically perturbing postural situations (see below) or during locomotion.

The absence of postural stabilization in the LGs condition is more surprising. Indeed, despite the reduction of available haptic information, we expected to observe a (even though smaller) stabilizing effect when the stick moved on a slippery surface as compared to a rough surface. This prediction corresponded to Jeka and Lackner (1995)'s findings about the equivalent stabilizing effect of a LT of the fingertip on surfaces with different frictional properties (i.e., slippery and rough). However, in their experiment, contrary to the present study, no relative movement between the finger and the support was observed. Furthermore our prediction was consistent in sense with results observed by Lackner et al. (2001). They revealed a smaller but significant stabilizing effect of flexible filaments that provided a smaller spatial stability and less resistance against body sway when compared to rigid filaments. It is equally possible, that body oscillations in the present study were too small to make the information resulting from the movements of the stick on the slippery surface detectable or functional for postural control. According to Riley et al. (1997), an alternative, though speculative, interpretation could be that large body oscillations performed in this condition would correspond to an exploratory strategy of participants in order to search for or to enhance haptic information.

Taken together, the present results lead to distinguish two groups of experimental conditions. They differ with respect to the presence or absence of haptic information that are functional for postural control. On the one hand, there are the conditions LGf, LGb and LGr, in which a resistance was offered against body oscillations by the fixed or mobile stick. This resistance presumably created sway-related transient contact forces on the fingers. On the other hand, there are the conditions QS, LGh and LGs, in which no resistance or an insufficient one was offered against body oscillations, due to the absence or the mobility of the support.

3.5.3. Effects of fixed- and mobile-support conditions in medio-lateral direction

Results observed in the ML direction across all but one condition of haptic supplementation diverged from those observed in the AP direction. As expected, stabilization observed in the ML direction significantly differed for the fixed- and mobile-support conditions. Indeed, the mobile-support conditions (LGb, LGs, LGr and LGh) failed to improve postural stability in this direction. Conversely, the fixed-support condition (LGf) led to a significant decrease in the range of postural oscillations. These findings can be explained by the absence of resistance against ML oscillations in the mobile-support conditions. Only in the AP direction sway-related haptic information were provided by the LG of the mobile stick, whereas no resistance against body oscillations was provided in the ML direction.

3.6. Conclusion

This first experiment addressed the issue of how haptic supplementation provided by a LG of a fixed or mobile stick influenced postural stability. The present experiment differed from previous light-touch studies with respect to at least three important aspects. First of all, sensory supplementation was provided by a LG with three fingers permitting to extend the usefulness of haptic supplementation to a more natural stick-use situation. Secondly, across the different conditions of haptic supplementation, the mobility of the handle and the extremity of the stick were manipulated independently in both the AP and ML directions, so that more or less resistance of the stick against body oscillations could be provided in both directions. Such strategy permitted to show that stabilizing effects result from sway-related changes in cutaneous and proprioceptive cues rather than from the presence of a fixed reference point. Indeed, no postural stabilization was observed in the ML direction when the stick handle was mobile that is, when no resistance was opposed against body sway. Third, by allowing the extremity of the stick to scratch on a slippery or a rough surface, we manipulated the resistance of the stick against body sway and, consequently, the haptic cues that were fed back to participants. Our results suggested that a given level of resistance opposed to body oscillations by the mobile stick (i.e., dynamic frictional coefficient > 0.37) is required to allow postural stabilization. Actually, beyond the stabilizing effect of the “classical” fixed-support condition (LGf) in the AP direction, the present results led to identify two mobile-support conditions (LGb and LGr) that stabilize posture independent of the nature of the support. More specifically, the LGr condition, in which both the handle and the extremity of the stick were free to move, was identified as equally effective to increase postural stability as the fixed-support condition (LGf). The observed postural stabilization in the LGr condition could either have occured 1) due to an enriched sensory environment during the LG, which helps therefore to better perceive self-motion (*supplementation*), or 2) due to dynamic sensory reweighting processes in the integration of orientation cues, which help to replace inaccurate or missing orientation cues from another “posture-specific” sensory modality (*substitution*).

However, the question still remained if the effect of haptic cues from a mobile stick also applies to older adults. If the postural control system during aging was altered at a peripheral or central level, this could prevent older adults from benefiting from haptic supplementation.

4. Study II: Haptic supplementation in young and older adults

4.1. Introduction

The results of the first study showed that the stabilizing effect of haptic supplementation on postural stability in a quiet-stance task of young adults is independent of the nature of the support (i.e., fixed or mobile stick). Given that sway-related haptic cues are provided to participants that inform about the motion of the body even the LG of a mobile stick improved postural stability. The resistance offered against body sway appeared to determine if haptic cues are perceivable or functional for postural stabilization.

Since aging is characterized by peripheral sensory loss (e.g., decreased plantar tactile sensitivity [Perry, 2006]) and alterations in central integration of multiple sensory cues, sensory reweighting is considered one of the most critical factors for postural control in older populations [Horak, 2006, Baccini et al., 2007, Menz et al., 2006, Rabin et al., 2008, Teasdale et al., 1991]. However, several studies showed a stabilizing effect of haptic supplementation from the LT on a fixed support on postural stability of healthy older adults [Baccini et al., 2007, Reginella et al., 1999, Tremblay et al., 2004] and older adults with neuropathies [Dickstein et al., 2001]. Thereby, these studies supported the hypothesis that the capacity of sensory reweighting remains, at least in part, preserved during aging [Allison et al., 2006]. Moreover, the effective use of sensory substitution [Danilov et al., 2007] or sensory enhancement [Gravelle et al., 2002, Priplata et al., 2003] underlined the capacity of older adults to make use of additional (or enhanced) sensory cues in order to compensate for potential age-related changes in the postural control system.

By using the same experimental paradigm than in the first study, the present study aimed at determining whether and how older adults can benefit from haptic supplementation provided by a mobile stick. Thus, according to Newell (1986)'s model, we manipulated the environmental (sensory cues) and the subject-related (age groups) factors of postural control, while choosing a simple quiet stance task. With this objective in mind, we compared different age groups, while controlling for the functional status of different postural control systems (healthy young and older adults).

In addition to the classical COP variables analyzed in study I (i.e., RMS and range), in the present experiment we further explored the effect of haptic supplementation on the underlying postural control mechanisms by using the power spectral analysis to determine frequency components of the body sway along with the SDA (see [Collins and De Luca, 1993, Collins et al., 1995], for detailed methods). It has been shown that, during upright standing, age-related changes in postural control mechanisms were associated with two kinds of behaviors. Some studies showed smaller COP amplitude and higher MPF of body sway [Carpenter et al., 2006, Vieira et al., 2009], presumably resulting from increased muscle activity and ankle stiffness. In contrast, others showed that older participants swayed more than younger participants [Horak, 2006, Baccini et al., 2007, Menz et al., 2006]. Moreover, higher MTP of the frequency spectrum of body sway has currently been observed in older adults [McClenaghan et al., 1996, Holden et al., 1994]. Thus, if haptic supplementation has a facilitating effect on postural control, one may observe decreased body sway and a shift towards higher MPF [Rabin et al., 1999] as well as lower MTP [Holden et al., 1994, Jeka and Lackner, 1994].

The SDA permitted to explore the effects of aging and haptic supplementation on open-loop and closed-loop control mechanisms of postural stability [Collins and De Luca, 1993]. Two regions of corresponding stabilogram diffusion plots can be discerned by the critical point (x-coordinate CPs and y-coordinate CPmm²) indicating the region of plots, where the slopes significantly changed. These two regions are hypothesized to correspond to open-loop and closed-loop control mechanisms, respectively [Collins and De Luca, 1993]. Specifically, the slopes of the straight lines fitted to these two regions (Ds and Dl) are hypothesized to correspond to the stochastic activity of the COP trajectory during open-loop and closed-loop control. Collins et al. (1995) showed that body sway of older adults was characterized by a greater Ds, later CPs and larger CPmm². These changes in open-loop parameters presumably reflected higher muscle activity and increased joint stiffness in older participants. Sullivan et al. (2009) observed that older adults benefited from sensory supplementation (such as LT or vision) reflected by decreased Ds (see also [Riley et al., 1997], for similar results in young healthy adults) and Dl. These findings suggested that additional sensory cues not only reduce the steady-state activity of the muscles during open-loop control, but also improve sensory integration processes that occur during closed-loop control.

4.2. Aims and hypotheses

Firstly, we expected to observe higher RMS, higher range and greater area of the COP in older than in young participants during quiet standing. We also predicted that haptic supplementation improves postural control in older adults independent of the nature of the (fixed or mobile) support under the condition that it offered sufficient resistance against the body sway. These results should be mainly observed in the AP direction, in which this resistance offered by the different supports was manipulated. The availability of haptic supplementation should also increase MPF [Rabin et al., 1999] and decrease MTP [Holden et al., 1994, Jeka and Lackner, 1994]. A decrease in Ds and consequently in $CPmm^2$ should be observed as a result of haptic supplementation as well as a decrease in Dl.

4.3. Materials and methods

4.3.1. Participants

Ten young (7 women and 3 men, mean age 25.8 years ± 1.9 years) and eleven older adults (6 women and 5 men, mean age 71 years ± 7.3 years) participated in the experiment. The older participants were recruited from a retirement club in Marseille, at which they were engaged in fitness activities twice a week. They lived independently and were in good health. All participants were right-handed, physically active and had no self-declared musculoskeletal injuries, or perceptive, cognitive and motor disorders that may have affected their ability to maintain balance or to understand task instructions. They had no prior experience with the task or the experimental apparatus. Informed consent to participate in the study was obtained from all participants. The protocol was approved by a local ethics committee and has therefore been in accordance with the ethical standards laid down in the declaration of Helsinki.

4.3.2. Task and experimental design

The participants stood on a force platform with EO, in conditions with or without haptic supplementation. The position of the participants and instructions given for the quiet upright stance were the same as in the previous study (study I, chapter 3.3.2.).

Haptic supplementation was provided through the LG of a stick with the right hand (chapter 2.4.1.). Six experimental conditions were tested (Figure 10): 1) quiet stance (QS), 2) a fixed- (LGf), 3) a horizontal- (LGh), 4) a blocked-support condition (LGb), 5) a slippery- (LGs) and 6) a rough-surface condition (LGr). In the horizontal-support condition (LGh) participants lightly gripped the stick at its longitudinal center and held it in a roughly horizontal position. This condition was similar to the horizontal-cane condition tested by Hausbeck et al. (2009). As the stick was not in contact with the ground, this condition presumably provided minimal transient sway-related inertial forces created by the hand-held (weight of the) stick. The mobility of the stick and its resistance to body oscillations in the AP direction were manipulated in four conditions of haptic supplementation (LGf, LGb, LGs and LGr). Participants did three trials of 30 s in each condition. Breaks lasted 30 s between each trial and 60 s between each condition. The experimental session lasted about 1 h.

4.3.3. Apparatus and measures

The force platform (AMTI, Advanced Mechanical Technology, Inc., MA, USA) measured the three components of the resultant ground reaction force to determine COP trajectories in the AP and ML directions. The sampling rate was set at 200 Hz. Data were acquired with LabView 7.5 (National Instruments®, Austin, TX, USA) on a PC and analyzed offline with Matlab 7.0 (The MathWork®, Inc., Natrick, MA, USA). The COP data were low-pass filtered (second-order Butterworth, 10 Hz, dual-pass). Classical COP variables (RMS, range and area) were calculated. Individual data were averaged for the three trials of the same condition.

COP trajectories were subjected to a Fast Fourier Transform with a frequency resolution of 0.03 Hz to determine frequency components of the body sway in the bandwidth between 0.06 and 5 Hz. The individual power spectra were averaged across trials for each condition serving as a spectral signature for further analysis. SDA was also performed on the COP trajectories. Stabilogram diffusion plots were created by plotting the mean squared displacements between COP data points separated in time as a function of corresponding time intervals (increasing from 0.005 s to 6 s at steps of 0.005 s). Stabilogram diffusion plots were averaged across the three trials for each condition, and the resultant plots were further analyzed. To find the critical point, the time interval in the range of 0.5 to 2 s was identified at which the summed residuals of pairwise linear regressions were minimal.

The following nine dependent variables were extracted from the COP trajectories in the AP and ML directions (only the area was estimated based on the planar COP displacement (AP versus ML)): 1) RMS [cm], 2) range [cm], 3) area [cm²], 4) MTP [cm²], 5) MPF [Hz], 6) CPs [s], 7) CPmm² [mm²], 8) Ds [mm²/s] and 9) Dl [mm²/s] (see chapter 1.1.2.).

Data was subjected to 2 (between-participant factor group) x 6 (within-participant factor condition) ANOVAs with repeated measures on the last factor. Normality was checked by means of Kolmogorov-Smirnov tests. All significant ANOVA effects were further analyzed using Newman-Keuls post-hoc tests (threshold of significance at $P<0.05$). The eta-squared (η^2) was used as a measure of effect size. η^2- values of 0.01 to 0.03, 0.06 to 0.09 and >0.14 indicate a small, medium and large effect, respectively [Cohen, 1988].

4.4. Results

Table 1 shows a summary of the results (mean and standard deviation, F- and effective p-values) of the main and interaction effects for all dependent variables. Though the results of the post-hoc tests are not reported in detail, the differences between experimental conditions that are described below were all significant or showed a trend ($P=0.06$).

4.4.1. Area of planar center of pressure displacement

The analysis of the area revealed an effect of group and condition. Older participants showed larger areas than younger participants. The area in the conditions QS, LGh, LGr and LGs did not differ significantly. In contrast, the area was significantly smaller in the condition LGf when compared to the conditions QS, LGh and LGs. A tendency for a difference between the conditions QS and LGb was also observed ($P=0.06$), whereas the area in the condition LGr did not significantly differ from the condition QS. The area in the three mentioned conditions of haptic supplementation (LGf, LGb and LGr) did not differ significantly from each other.

4.4.2. Analysis of center of pressure trajectories in the antero-posterior direction

The analysis of the RMS revealed an effect of condition. The RMS observed in the conditions QS, LGh and LGs did not differ significantly from each other. In contrast, the RMS observed in the conditions QS, LGh and LGs was significantly higher than in the conditions LGf, LGb and LGr. The analysis did not reveal a significant difference between the conditions LGf, LGb and LGr.

The analysis of the range revealed an effect of group and an effect of condition. The range of older participants was larger than those of younger participants (Figure 15 left). The range observed in the conditions QS, LGh and LGs did not differ significantly from each other. In contrast, the range observed in the conditions QS, LGh and LGs was significantly higher than in the conditions LGf, LGb and LGr (Figure 15 right). No significant difference was observed between the conditions LGf, LGb and LGr.

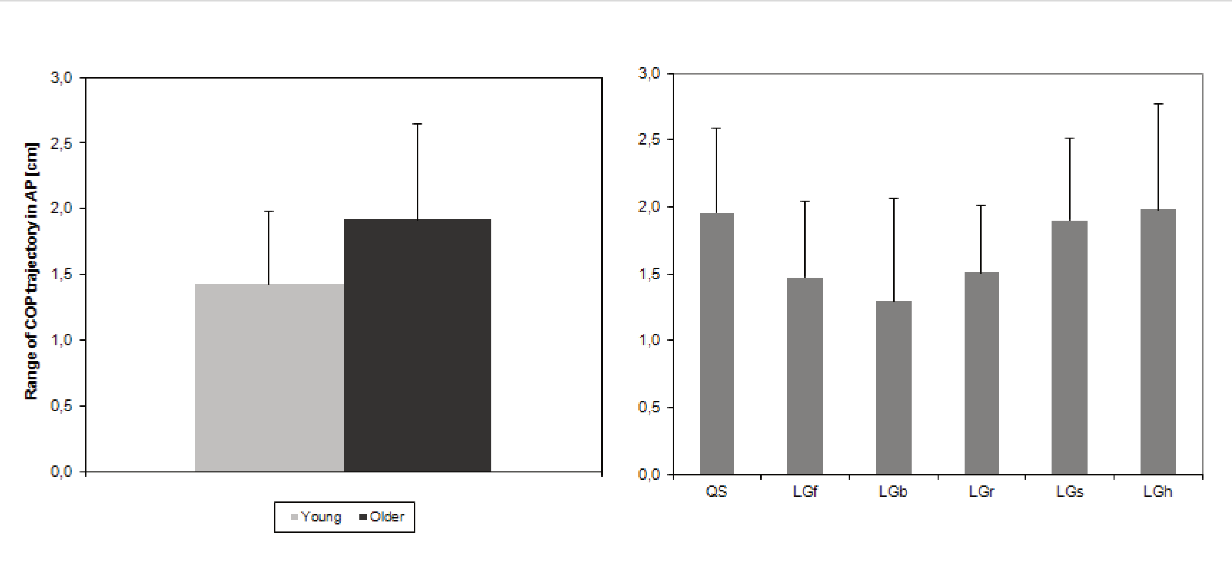

Figure 15: Range of the COP (means and standard deviation) in the AP direction that is, in the most unstable plane, of young and older participants (on the left) and in the six experimental conditions (on the right)

The analysis of the MTP revealed an effect of group and an effect of condition as well as an interaction effect of group and condition (Figure 16). The post-hoc decomposition of the interaction effect revealed significantly higher MTP in the conditions QS and LGh than in the conditions LGf, LGb, LGr and LGs in older participants (Figure 16). MTP in the conditions LGf, LGb and LGr was significantly lower than in the condition LGs in older participants. No significant difference was observed between the conditions QS and LGh, between the conditions LGh and LGs and between the conditions LGf, LGb and LGr in the group of older participants. In younger participants, no significant difference was observed between conditions.

The analysis of the MPF revealed an effect of condition. The MPF observed in the conditions LGf, LGb, and LGr was higher than in the conditions QS, LGh and LGs, which did not differ significantly from each other. Similarly, the conditions LGf, LGb and LGr did not differ significantly from each other.

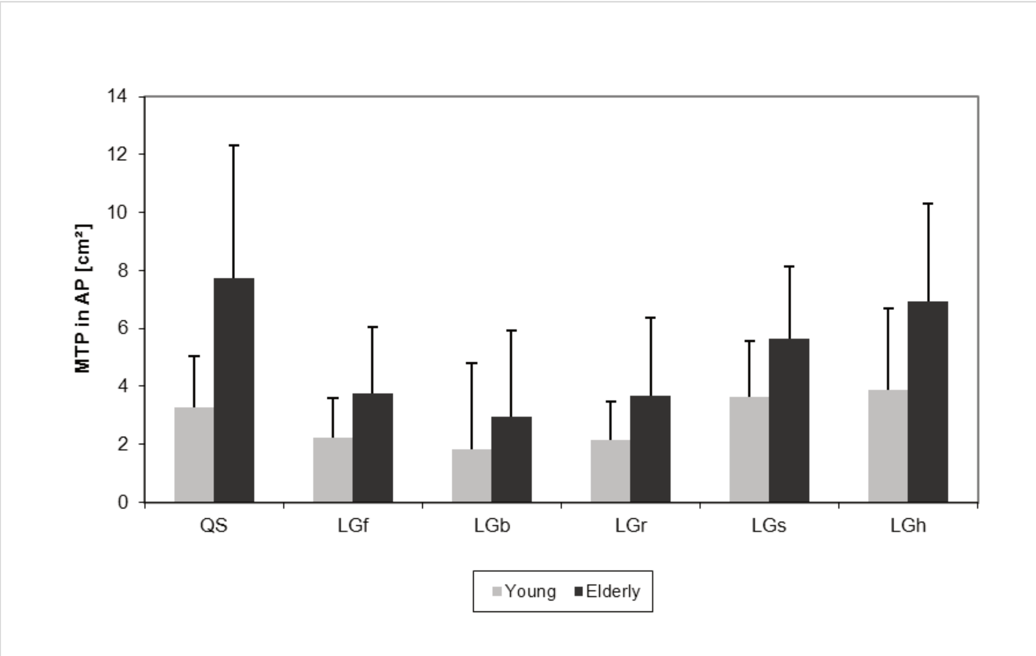

Figure 16: MTP of the COP in the AP direction that is, in the most unstable plane, of young and older participants (means and standard deviation)

The analysis of the Ds revealed an effect of group and an effect of condition. Older participants showed higher Ds than younger participants (Figure 17). The Ds was significantly higher in the condition LGh than in the conditions QS, LGf, LGb, LGr and LGs, that did not differ significantly from each other. The analysis of the Dl revealed an effect of condition. The Dl was significantly lower in the conditions LGf, LGb and LGr than in the conditions QS, LGh and LGs, that did not differ significantly from each other.

The analysis of the CPs revealed an effect of group. Older participants showed greater CPs than younger participants (Figure 17). The analysis of the CPmm² revealed an effect of group and an effect of condition. Older participants showed greater CPmm² than younger participants (Figure 17). The CPmm² in the conditions QS, LGh and LGs was significantly higher than in the conditions LGf, LGb and LGr, that did not differ significantly from each other nor from the condition LGs.

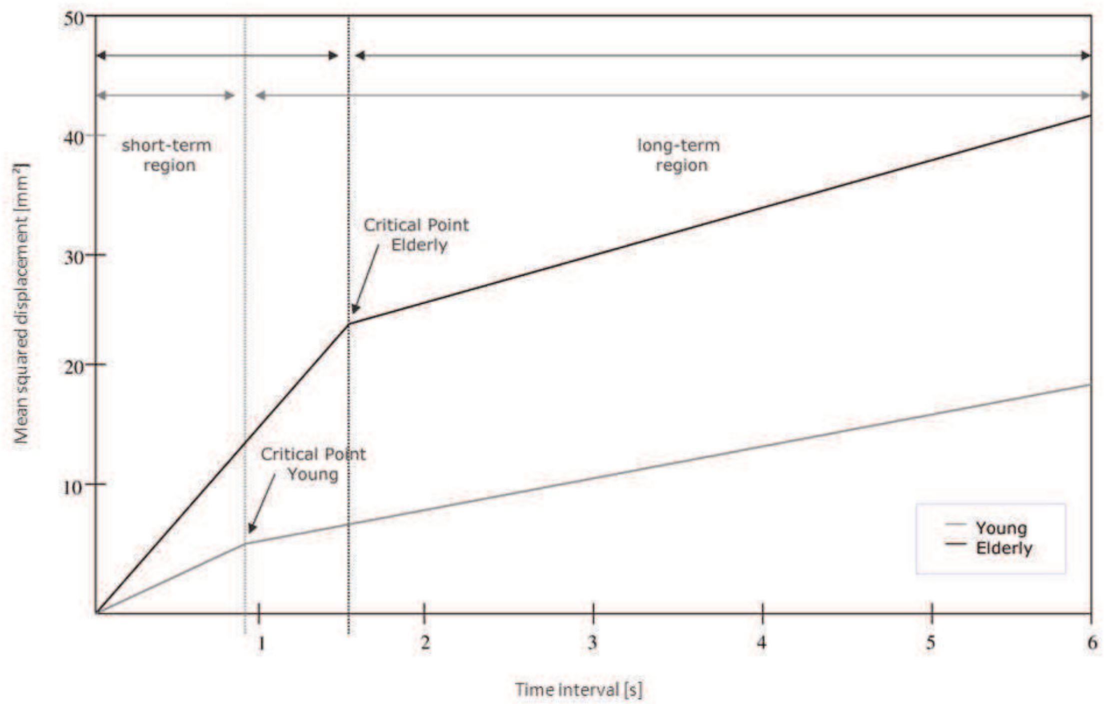

Figure 17: Schematic representation of the stabilogram diffusion plot in the AP direction for the different age groups
The critical point of older adults is situated later in time and at larger critical mean squared displacements

4.4.3. Analysis of center of pressure trajectories in the medio-lateral direction

The analysis of the RMS revealed an effect of group and an effect of condition. Older participants showed higher RMS than younger participants. The RMS observed in the LGf condition was lower than those observed in the conditions QS, LGh, LGb and LGr, that did not differ significantly from each other. Moreover, the conditions LGs and LGf showed a tendency to differ significantly (P=0.06).

The analysis of the range revealed an effect of group and an effect of condition. The range was larger for older than for younger participants. The range observed in the LGf condition was significantly lower than those observed in the conditions QS, LGh, LGb and LGs, that did not differ significantly from each other. The conditions LGr and LGf showed a tendency to differ significantly (P=0.06).

The analysis of the MTP revealed an effect of group and an effect of condition. The older participants showed significantly higher MTP than younger. The MTP was significantly lower in the condition LGf than in the condition LGh. Moreover, post-hoc decomposition of the condition effect showed a tendency for a significant difference between LGf and LGb (P=0.06).

The analysis of the MPF revealed an effect of group and an effect of condition. Older participants showed lower MPF than the young participants. The MPF observed in the condition LGf was higher than in the conditions QS, LGh, LGb, LGr and LGs, which did not differ significantly from each other.

The analysis of the Ds revealed an effect of group. Older participants showed higher Ds than younger participants. The analysis of the Dl revealed an effect of group, an effect of condition and an interaction effect of group and condition. The post-hoc decomposition of the interaction effect did not reveal a significant difference between conditions for young participants. In contrast, for older adults, Dl were significantly higher in the condition LGh than in the conditions QS, LGf, LGb, LGr and LGs. The latter conditions (QS, LGf, LGb, LGr and LGs) did not differ significantly from each other.

The analysis of the CPs revealed an effect of group. Older participants showed longer CPs than younger participants in all conditions. The analysis of the CPmm² revealed an effect of group and an effect of condition. Older participants showed greater CPmm² than younger participants in all conditions. Moreover, the CPmm² was significantly lower in the condition LGf than in the conditions LGh and LGb.

4.5. Discussion

This experiment aimed to test the effect of different conditions of haptic supplementation provided by a LG of a fixed or mobile stick of healthy older adults during quiet upright stance. The results confirmed our general hypothesis that older adults can make use of haptic cues provided by the LG of a mobile stick.

4.5.1. Age-related changes in postural control

Classical COP variables indicated that older participants were less stable than their younger counterparts. Indeed, they showed higher RMS (in the ML direction), higher range (in the AP and ML directions) and larger area of the COP displacement than young participants. These findings are not surprising (see [Horak, 2006, Baccini et al., 2007, Menz et al., 2006], for consistent results) but they were a prerequisite for the investigation of age-related effects of haptic supplementation.

No difference was found between young and older participants concerning MPF in the AP direction. In contrast, older participants in the ML direction showed lower MPF than young participants (0.36 Hz and 0.43 Hz, respectively). These results differed from previous studies, which showed higher MPF and decreased body sway in older participants, presumably due to an age-related strategy of increased ankle joint stiffness [Carpenter et al., 2006, Vieira et al., 2009]. Thus, our results suggested that the two age groups use a similar postural control strategy in AP direction, while only older participants in the ML direction presumably use slow lateral weight shifts to stabilize the upright position [McClenaghan et al., 1996].

Table 1: Mean values of the variables extracted from COP trajectories for the two age groups and the six experimental conditions

Variable	GROUP					CONDITION								
			p	η2	F-value							p	η2	F-value
	Young	Older				QS	LGf	LGh	LGb	LGr	LGs			
Area [cm²]	0.63 (0.40)	1.34 (1.08)	**	.16	F(1,19)=6.76	1.25 (0.89)	0.61 (0.51)	1.38 (1.16)	0.81 (0.90)	0.87 (0.73)	1.09 (0.94)	***	.08	F(5,95)=5.30
RMS AP [cm]	0.30 (0.13)	0.39 (0.16)				0.41 (0.13)	0.3 (0.12)	0.41 (0.17)	0.26 (0.11)	0.32 (0.13)	0.4 (0.18)	***	.16	F(5,95)=11.46
Range AP [cm]	1.43 (0.56)	1.92 (0.73)	*	.13	F(1,19)=4.68	1.95 (0.63)	1.47 (0.57)	1.98 (0.77)	1.29 (0.50)	1.51 (0.62)	1.9 (0.72)	***	.15	F(5,95)=13.70
MTP AP [cm²]	2.83 (2.19)	5.12 (3.53)	*	.13	F(1,19)=5.72	5.61 (4.13)	3.02 (2.03)	5.46 (3.30)	2.15 (2.30)	2.96 (2.30)	4.70 (3.23)	***	.16	F(5,95)=12.59
Young *Older*						*3.27 (1.77)* *7.75 (4.56)*	*2.22 (1.38)* *3.75 (2.29)*	*3.86 (2.96)* *6.92 (2.99)*	*1.84 (1.31)* *2.94 (2.66)*	*2.16 (1.91)* *3.69 (2.47)*	*3.63 (2.83)* *5.66 (3.39)*	*	*.03*	*F(5,95)=2.68*
MPF AP [Hz]	0.39 (0.11)	0.37 (0.10)				0.31 (0.05)	0.41 (0.09)	0.34 (0.09)	0.45 (0.15)	0.41 (0.08)	0.35 (0.08)	***	.22	F(5,95)=8.70
Ds AP [mm²]	8.64 (8.93)	15.4 (8.25)	*	.14	F(1,19)=4.88	12.68 (6.43)	11.17 (6.61)	16.71 (13.35)	9.91 (6.49)	11.38 (11.19)	11.26 (8.28)	**	.06	F(5,95)=3.90
Dl AP [mm²]	2.08 (2.42)	2.99 (2.02)				3.19 (2.70)	1.64 (1.46)	3.75 (2.53)	1.39 (1.44)	2.13 (1.57)	3.24 (2.55)	***	.15	F(5,95)=7.40
CPs AP [s]	0.96 (0.96)	1.64 (0.55)	**	.16	F(1,19)=9.13	1.40 (0.88)	1.20 (0.68)	1.31 (0.69)	1.35 (0.66)	1.22 (1.11)	1.43 (1.02)			
CPmm² AP [mm²]	6.37 (7.32)	25.94 (11.76)	***	.50	F(1,19)=28.82	19.47 (18.41)	14.9 (13.17)	19.79 (12.89)	14.25 (12.40)	14.83 (13.19)	16.48 (13.08)	**	.03	F(5,95)=3.56
RMS ML [cm]	0.18 (0.08)	0.27 (0.14)	*	.14	F(1,19)=5.85	0.24 (0.11)	0.17 (0.09)	0.26 (0.14)	0.25 (0.15)	0.22 (0.11)	0.23 (0.13)	**	.06	F(5,95)=3.16
Range ML [cm]	0.93 (0.41)	1.31 (0.68)	*	.10	F(1,19)=4.00	1.25 (0.57)	0.83 (0.42)	1.31 (0.75)	1.16 (0.65)	1.11 (0.52)	1.1 (0.59)	**	.06	F(5,95)=3.41
MTP ML [cm²]	1.39 (1.10)	2.98 (3.03)	*	.11	F(1,19)=5.50	2.55 (2.33)	1.15 (1.03)	2.89 (3.23)	2.71 (3.24)	2.02 (1.88)	2.04 (2.09)	*	.05	F(5,95)=2.25
MPF ML [Hz]	0.43 (0.09)	0.36 (0.09)	**	.14	F(1,19)=9.54	0.38 (0.10)	0.46 (0.09)	0.37 (0.13)	0.39 (0.10)	0.39 (0.07)	0.37 (0.09)	***	.10	F(5,95)=4.18
Ds ML [mm²]	5.82 (4.79)	9.22 (4.50)	*	.12	F(1,19)=4.53	8.54 (5.38)	6.04 (4.03)	8.41 (5.45)	7.97 (4.91)	7.14 (4.43)	7.53 (5.35)			
Dl ML [mm²]	0.52 (0.61)	1.37 (1.48)	***	.12	F(1,19)=13.66	0.68 (0.53)	0.49 (0.51)	1.72 (2.15)	1.17 (1.23)	0.93 (0.82)	0.78 (1.00)	**	.10	F(5,95)=3.53
Young *Older*						*0.58 (0.63)* *0.77 (0.43)*	*0.32 (0.59)* *0.65 (0.38)*	*0.65 (0.75)* *2.7 (2.55)*	*0.47 (0.61)* *1.81 (1.33)*	*0.68 (0.62)* *1.16 (0.93)*	*0.45 (0.52)* *1.09 (1.23)*	*	*.07*	*F(5,95)=2.57*
CPs ML [s]	0.78 (0.35)	1.27 (1.30)	***	.16	F(1,19)=15.11	0.91 (0.55)	0.83 (0.21)	1.06 (0.41)	1.67 (2.21)	0.91 (0.33)	0.84 (0.43)			
CPmm² ML [mm²]	4.37 (3.86)	10.7 (6.34)	***	.27	F(1,19)=20.80	8.34 (7.58)	5.16 (3.71)	9.07 (7.24)	9.6 (6.55)	7.23 (5.55)	6.73 (5.09)	*	.06	F(5,95)=2.68

Note. Mean and standard deviation in brackets, F- and η2- values for significant (p<0.05, **p<0.01, ***p<0.001) main or interaction effect (cursive)*

The MTP was higher in older than in young participants in the AP and ML directions. This result suggested that postural control is more energy consuming in older participants [McClenaghan et al., 1996], presumably due to an increase in muscle activity and/ or co-contraction of antagonistic lower limb muscles [Laughton et al., 2003]. The SDA also suggested an age-related increase in muscle activity. Specifically, in older participants, the Ds increased in the AP and ML directions. These findings were consistent with the results previously observed by Collins and colleagues (see [Collins et al., 1995, Sullivan et al., 2009], for consistent findings in old men). They indicated higher open-loop stochastic activity in older than in young participants, presumably due to an age-related difference in the steady-state activity levels of the ankle muscles during open-loop postural control [Collins et al., 1995]. In support of this hypothesis, Laughton et al. (2003) found a positive correlation between the increase in muscle activity and co-contraction measured via electromyography and the increase in the Ds. It is noticeable however that neither body sway decreased nor the MPF increased in older participants, as expected if an ankle stiffening strategy was used. A possible explanation is that the increased muscle activity permits enhancing joint proprioception [Laughton et al., 2003, Cordo et al., 1996], rather than “mechanically” stiffening the ankle joint. Nevertheless, this did not compensate for age-related perceptual deficits, as longer critical time intervals and higher critical mean squared displacement were observed in older participants in the AP and ML directions (see [Collins et al., 1995, Sullivan et al., 2009], for consistent findings in old men). These results indicated a delayed switch from open-loop to closed-loop mechanisms during postural control in older participants, which could result from an age-related loss of proprioception [Collins et al., 1995, Goble et al., 2009].

4.5.2. Effect of haptic supplementation on postural control

The results showed that haptic supplementation was equally effective to increase postural stability in both groups of participants (see [Reginella et al., 1999, Tremblay et al., 2004], for consistent results with a fixed support). In the AP direction, a decrease of the RMS and the range were observed in the three conditions of haptic supplementation 1) LGf (fixed support), 2) LGb (mobile support in the ML but fixed on the ground in the AP direction) and 3) LGr (mobile support on a rough surface). As already shown in the first study, no stabilization was observed in two other conditions of haptic supplementation (LGh and LGs), which challenged the interpretation of goal-oriented postural organization toward the supra-postural task in order to better achieve the LG of the stick [Albertsen et al., 2010, Riley et al., 1999]. Instead, they suggested that these conditions of haptic supplementation (i.e., including those delivered by a mobile support) provide sway-related changes in contact forces on the fingertip and upper limb proprioception [Krishnamoorthy et al., 2002, Lackner et al., 2001]. Similar to the first study, the results suggested that when haptic supplementation is provided by a mobile support (LGb and LGr), the cognitive process of spatial orientation (with respect to a fixed reference frame in the environment) may be substituted by sensorimotor processes based on the integration of additional haptic cues arising from the light resistance opposed to body sway by the support [Albertsen et al., 2010]. The results observed in the ML direction are consistent with this hypothesis. Indeed, postural stabilization was only observed in the fixed-support condition of haptic supplementation (LGf) that is, in the only condition providing sway-related haptic cues in the ML direction by opposing a resistance to ML body sway. Finally, even though tactile acuity at the level of the fingertip is commonly known to decrease during normal aging [Tremblay et al., 2004], haptic information appeared to be efficiently integrated by older participants in postural control. Indeed, they benefit from haptic supplementation (from fixed or mobile supports) to the same extent as young adults, though without fully compensating for age-related alterations of postural control.

The availability of haptic supplementation in the AP direction shifted the MPF towards higher values (~ 0.4 Hz) in the conditions LGf, LGb and LGr relative to QS (~ 0.3 Hz). In the ML direction, this shift only occurred in the fixed-support condition of haptic supplementation (LGf). These results are consistent with those observed for other COP variables. They suggested that this slight shift in MPF results from haptic supplementation [Rabin et al., 1999]. Taken together, the observed decrease in COP displacements due to haptic supplementation (LGf, LGb, LGr in AP and LGf in the ML direction) and the shift towards higher MPF may indicate that postural stabilization results from an increase in muscle activity around the ankle joint. However, the results observed for MTP challenges this interpretation. In fact, in older participants, haptic supplementation (LGf, LGb, LGr and LGs) in the AP direction was accompanied by a decrease in MTP (see [Holden et al., 1994, Jeka and Lackner, 1994], for consistent results). As a result, the previously observed age-related difference in MTP during quiet stance was attenuated. Thus, in older participants, haptic supplementation appeared to improve postural stability by decreasing the energy consumed to control body sway. To our knowledge, such positive effect of haptic supplementation in older adults has never been reported in the literature. This decrease in energy expenditure could presumably be obtained by decreasing muscle activity around the ankle joint. Results previously observed by Jeka and Lackner (1995) strengthen this interpretation, as they showed reduced body sway together with reduced levels of EMG activity (~50%) of lower limb muscles due to LT. Consequently, such changes in muscle activity may permit participants to tune postural control on the frequency-specific sensors of sensory systems predominantly involved in the postural task. In other words, the participants may adopt an optimal sway frequency in order to better perceive haptic cues.

A striking result was that, in older participants, MTP significantly decreased in the AP direction in the LGs condition, though no stabilizing effect was observed for classical COP variables. Therefore, power spectral analysis might be better suited than classical COP analyses to detect small improvements in postural control gained by haptic supplementation. This result suggested that older adults are sensitive to very small changes in contact forces and proprioceptive cues evoked by the LG of the mobile support, even if it provides only minimal resistance (LGs). Another possible explanation might be that older participants sway more and consequently perceive larger changes in haptic cues than younger participants (see [Baccini et al., 2007], for a consistent interpretation).

The results of the SDA also suggested a decrease in muscle activity due to haptic supplementation. Indeed, in the AP direction, haptic supplementation led to decreased critical mean squared displacement in both age groups, independent of the nature of the support (LGf, LGb and LGr). In other words, due to haptic supplementation, the COP travelled smaller distances than in the reference condition (QS) before closed-loop corrections could be accomplished. These results suggested that haptic supplementation reduces the steady-state activity level of the postural muscles around the ankle to control the upright posture [Collins and De Luca, 1993, Collins et al., 1995].

Furthermore, in the present study, the Dl in the AP direction decreased independent of the stability of the haptic support (LGf, LGb and LGr) in both age groups (see [Sullivan et al., 2009], for consistent results). These findings suggested that participants reduce the closed-loop stochastic activity of the COP due to the integration of additional haptic cues, a sign for improved closed-loop feedback mechanisms of postural control. Taken together, our results suggested that haptic supplementation affects both open-loop and closed-loop postural control mechanisms and results in decreased body sway. Finally, this stabilizing effect is independent of age and the stability of the haptic support.

4.6. Conclusion

The present study showed that aging leads to more variable body sway, to deficits in open-loop control mechanisms and to increased MTP associated with postural control. In contrast, they also showed that haptic supplementation is equally effective to improve postural stability in both age groups. Consequently, the CNS can integrate sway-related haptic cues from transient contact forces and arm proprioception in postural control even in the absence of a fixed reference point in the environment (LGb and LGr). This stabilizing effect occurs under the condition that sufficient resistance is opposed to body sway by the haptic support (by blockade or rough surface). Moreover, our results suggested that haptic supplementation reduces (over short time intervals) the reliance on increased muscle activity around the ankle and leads (after longer time delays) to well-coordinated postural corrections. However, it only permits older participants to spare energy during the postural task, even in case the haptic support provides only minimal resistance (LGs) to body sway. As compared to the first study [Albertsen et al., 2010], the use of methods such as power spectral analysis and SDA, together with classical COP variables, significantly added to the understanding of the influence of haptic supplementation on sensorimotor processes of postural control.

Postural control mechanisms have been rarely compared between the two postural tasks of standing and sitting. We will explore this issue in the following study by applying the light-grip paradigm to an unstable sitting situation. In addition, we aimed to investigate if haptic supplementation provided by a mobile support can compensate for missing visual cues during unstable sitting. This kind of compensatory mechanisms between “posture-specific” (visual) and “non-posture specific” (haptic) cues have already been shown during quiet upright stance by the use of a fixed light-touch support [Jeka and Lackner, 1994]. The question however remained if haptic cues from a mobile support can play an equally important role as vision during postural control.

5. Study III: Postural control of sitting

5.1. Introduction

Postural control is a key function for both upright standing and sitting. Though biomechanically different, both the standing and the sitting postural systems are currently modelled as a single-link inverted pendulum rotating around the ankle [Maurer and Peterka, 2005, Peterka, 2000] or hip [Cholewicki et al., 2000, Reeves et al., 2007], respectively. Hence, similar feedback control models have been proposed to account for postural control in both standing and sitting [Kiemel et al., 2008, Reeves et al., 2007]. These models include two main components contributing to the system's stability - a plant and a controller. The plant represents the biomechanical structure that has to be controlled. The controller generates the input to the plant needed to achieve the desired output that is, upright standing or sitting, with different time delays [Alexandrov et al., 2005]. For this purpose it is provided with a variety of signals (proprioceptive, vestibular and visual). To study the functioning of the controller, classical experimental manipulations are sensory withdrawal or perturbations as they are currently used in studies of standing [McCollum et al., 1996, Peterka, 2002, Black et al., 1982] and sitting [Radebold et al., 2001, Silfies et al., 2003]. Haptic supplementation is a complementary experimental manipulation that has been used in the previous studies of the present work and in various studies of standing [Holden et al., 1994, Jeka and Lackner, 1994, Krishnamoorthy et al., 2002, Albertsen et al., 2010, Albertsen et al., 2012]. In the present study, we applied this technique to study the control of upright sitting. More specifically, we explored the role of "posture-specific" visual and supplementary "non-posture-specific" haptic cues in the control of unstable sitting in young and older adults. Thus, according to Newell (1986)'s model, we manipulated the environmental (sensory cues), the subject-related (age groups) and the task-inherent (sitting posture) factors of postural control. Findings of our previous studies suggested the importance of sway-related haptic cues from a mobile stick that enhance self-motion perception and thereby improve postural stability during quiet upright standing. Following the lead of these studies, here we studied the effect of haptic supplementation provided by a LG with a fixed or a mobile support on sitting postural control.

It is well known that aging alters the efficiency of sensory systems, central processing and postural muscles, thereby leading to a deterioration of postural control during upright standing [Horak, 2006, Teasdale et al., 1991]. The influence of normal aging on performance in functional tasks such as sit-to-stand has been also well-studied [Mourey et al., 1998, Nadeau et al., 2008]. However, age-related changes in sitting postural control mechanisms have received almost no attention. Nevertheless, one should expect age-related alterations of postural control in this task as well.

In upright-standing studies, it has been demonstrated repeatedly that additional sensory cues compensated for age- or disease-related postural instability of healthy older adults [Albertsen et al., 2012, Baccini et al., 2007, Reginella et al., 1999, Tremblay et al., 2004] and older adults suffering from neuropathies [Menz et al., 2006, Dickstein et al., 2001] or bilateral vestibular loss [Lackner et al., 1999]. According to common principles of postural control models for sitting and standing, one would expect to observe a stabilizing effect of haptic supplementation during unstable sitting as well. Considering, however, the effective complexity of the spine and the prominent role of muscle spindles and various other mechanoreceptors embedded in the spinal tissue to monitor spinal position and velocity [Reeves et al., 2007], this expectation has to be put to test.

A particular focus of the present study was on the effect of haptic supplementation on postural control mechanisms with different time delays. For this type of problem, the SDA is a suitable COP analysis. It has been proposed by Collins and De Luca (1993) for postural control of upright standing and applied to postural control of sitting [Cholewicki et al., 2000, Radebold et al., 2001, Silfies et al., 2003]. According to Collins and De Luca (1993), an age-related increase in Ds and Dl indicate higher open-loop and closed-loop stochastic activity and can be explained by higher activation of postural muscles needed to control a rather unstable system. Conversely, smaller diffusion coefficients and thus reduced open-loop and closed-loop stochastic activity have been found by Silfies et al. (2003) when vision was available during unstable sitting as compared to conditions without vision and by Sullivan et al. (2009) when vision or touch was available during upright standing.

5.2. Aims and hypotheses

Taken all considerations together, the present experiment was designed to test the following hypotheses. First of all, we expected that postural stability during upright sitting is reduced in older adults and that visual deprivation would reduce postural stability of both young and older participants, but more so in the older ones. Second, we expected that sway-related haptic cues improve postural stability during unstable sitting and compensate for the effects of age and visual deprivation. Third, haptic supplementation should mainly influence feedback control mechanisms that is, the long-term region of stabilogram diffusion plots so that Dl are reduced. However, as mentioned above, there is also evidence from postural control studies of upright sitting and standing that available sensory cues can affect the short-term region of stabilogram diffusion plots [Silfies et al., 2003, Sullivan et al., 2009].

5.3. Materials and methods

5.3.1. Participants

Fifteen young (7 women and 8 men, mean age 25.8 ± 2.6 years) and fifteen older adults (7 women and 8 men, mean age 66.2 ± 3.3 years) participated in the experiment. All participants were right-handed, physically active, and had no self-declared musculoskeletal injuries, or sensory, cognitive or motor disorders. Participants had no prior experience with the task or the experimental apparatus. They had given informed consent prior to the start of the experiment which was done in accordance with the ethical standards laid down in the declaration of Helsinki.

5.3.2. Cognitive and clinical tests

At the beginning of the experiment, the participants were tested for fluid and crystallized intelligence by means of the Digit Symbol Test of the German version of the WAIS [Tewes, 1991] and the Vocabulary Test [Schmidt and Metzler, 1992], respectively. In addition, two clinical tests of cutaneous spatial acuity at the fingertip were administered by means of a device with two outer spikes of adjustable gap width of 1 to 25 mm (Touch-Test® Two-Point Discriminator, NC12776, North Coast Medical, Inc.). A static and a moving test (tapping slow- and fast-adapting mechanoreceptors, respectively) consisted each of four test series, in which participants judged whether one or two spikes had been applied to their skin in order to determine the minimal distance between two stimulation points that they were able to segregate perceptually. A touch score in each test was calculated as the mean of the four minimal perceived distances [mm].

5.3.3. Task and experimental design

Six experimental conditions were tested (Figure 11): quiet sitting (QS), rocker-board sitting (SIT) and four conditions of haptic supplementation (a fixed-pen and three mobile-pen conditions). During QS, participants sat directly in the center of the force platform. In all conditions, participants were asked to maintain a natural erect sitting posture with their hips and knees flexed by 90°, to sit as stable as possible without moving their feet and legs and to cross arms in front of the chest. Their feet were unsupported. They were asked to fixate a point at eye height at 1.5 m on the wall. Adhesive tape was used to mark participant's buttocks position on the force platform so that the same task configuration was repeated each trial. During SIT, participants sat in the center of a rocker board on top of an elevated force platform. The rocker board destabilized participants in the ML direction. Haptic supplementation was provided through the LG of a pen with the right hand (chapter 2.4.2.). Thus, in all conditions of haptic supplementation only the left arm had to be held in front of the chest and participants sat on the rocker board with the fixed or mobile support orientated in the plane of greatest instability that is, in the ML direction. The mobility of the pen and its resistance against body sway were manipulated in four conditions of haptic supplementation: 3) a fixed- (LGf; Figure 18 left), 4) a blocked-support condition (LGb), 5) a slippery- (LGs) and 6) a rough-surface condition (LGr).

Figure 18: Sitting position of participants on the rocker board in the LGf condition (on the left) and the rocker board on the elevated force platform (on the right)

Figure 18 (left) shows the posture of the straight arm, holding the pen in contact with the digitizer tablet. In all conditions, the pen was out of sight of participants. During familiarization, participants could make use of an online display of the applied pen force on a monitor and an acoustic signal that sounded if the force threshold (< 1.2 N) was exceeded. Participants did four trials of 45 s duration with EO and four trials with EC. Half of the participants started with the four trials with EO and the other half with the four trials with EC. Breaks between trials lasted 30 s, breaks between conditions 60 s. Two wooden blocks served to immobilize the rocker board during these periods. The total experimental session lasted 2 h (about 1.5 h for the actual sitting task).

5.3.4. Apparatus and measures

A rocker board (41 cm x 41 cm of 1.2 cm thick Plexiglas®, bearing surface in 8.2 cm height, 27.9 cm radius of segment of circle, 1 DoF in the ML direction, Figure 18 right) was placed on a customized piezoresistive force platform (40 x 60 x 10 cm) that measured the three components of the resultant ground reaction force to determine the COP trajectories. The force platform was mounted on top of a rigid table in 68 cm height.

A digitizer tablet (Intuos4, Wacom Company Ltd.) was mounted on top of a table with adjustable height. The pen and digitizer were connected to a PC indicating by an acoustic signal when applied forces exceeded a threshold of 1.2 N.

Data were collected on a PC using the additional Psychtoolbox (Version 3.08) by means of an AD-converter (NI USB 6009, National Instruments®, Austin, TX, USA) at a sampling rate of 100 Hz. Data were analyzed offline with Matlab 7.5 (R2007b, The MathWork®, Inc., Natrick, MA, USA). The first 3 and the last 9 s of each trial were neglected and 33 s of the sampled data were analyzed. The time-series of COP positions were detrended, normalized by subtraction of the mean and low-pass filtered (second-order Butterworth, 10 Hz, dual-pass). Classical COP variables (RMS for the ML and AP directions, MV) were calculated for each trial and averaged across the four trials of each condition. SDA was also performed on the COP trajectories ([Collins and De Luca, 1993, Collins et al., 1995], for detailed methods). Stabilogram diffusion plots were created by plotting the mean squared displacements between COP data points separated by certain time intervals as a function of those intervals (increasing from 0.01 s to 8 s at steps of 0.01 s). Stabilogram diffusion plots were averaged across the four trials for each condition and the resultant plots were further analyzed. To find the critical point, the time interval in the range of 0.5 to 2 s was identified at which the summed residuals of pairwise linear regressions were minimal. The following dependent variables were extracted from the COP trajectories: 1) RMS for the ML and AP directions [cm]; 2) MV [cm/s]; 3) Ds [mm²/s]; 4) Dl [mm²/s]; 5) CPs [s] and 6) CPmm² [mm²] (see chapter 1.1.2.). In addition, the following dependent variables were extracted from the pen trajectories: 7) the standard deviation of the pen positions both for the ML and AP directions [mm], 8) the area covering 95% of the AP-ML pen displacement [mm²] [Duarte and Zatsiorsky, 2002], 9) the mean force applied by the pen [N].

The individual data were entered into statistical analyses. These were three-way ANOVAs with the between-participant factor group (young vs older) and the within-participant factors eyes (open vs closed) and condition (QS, SIT, LGf, LGb, LGr and LGs). Normality was checked by means of Kolmogorov-Smirnov tests. In the analysis of mean force applied by the pen only four of the six conditions were included (LGf, LGb, LGr and LGs), and in the analyses of the variability and the area of the pen displacement only two (LGr and LGs). Significant effects were further analyzed using Newman-Keuls post-hoc tests (threshold of significance at P=0.05). We used t-tests (or U-tests when data were not normally distributed) for the analysis of the cognitive and clinical tests.

5.4. Results

Mean performance of the two age groups in the clinical and cognitive tests is presented in Table 2. Performance of older participants was significantly lower in the Digit Symbol Test and significantly better in the Vocabulary Test than performance of young participants. The static and moving Two Point Discrimination Tests showed both a significantly lower sensitivity of older participants.

Table 2: Comparison of the two age groups in two cognitive and two clinical tests (means and standard deviation in brackets)

Test	Young	Old	t-test	U-test
Digit Symbol	69 (12.9)	51.9 (7.8)	$p = 0.0002$	
Vocabulary	30.1 (2.4)	33.1 (2.1)	$p = 0.0013$	
static Two Point [mm]	2.8 (0.5)	3.8 (1.4)	$p = 0.0155$	
moving Two Point [mm]	2.4 (0.6)	3.4 (1.5)		$p = 0.0055$

In the following, we will first present the effects of the rocker board on postural stability of young and older participants. Thereafter the effects of visual deprivation and of haptic supplementation will be described. Finally, we will report the effects of the variation of haptic cues across the different support conditions. A summary of the results (mean, standard deviations, F- and p-values) is provided in Table 3. Though the results of the post-hoc tests are not reported in detail, the differences between experimental conditions that are described below were all significant or showed a trend (P=0.06). In the present study, there was no generalized effect of age on any of the variables used to characterize postural stability.

Table 3: Results summary for variables extracted from the COP trajectories, the pen displacements and the applied pen force

Variable		Levels of factors	Condition						ANOVA results							
			QS	SIT	LGf	LGb	LGr	LGs	Effect	df	F	p	Effect	df	F	p
RMS ML	Young	EO	0.06 (0.01)	0.17 (0.10)	0.09 (0.03)	0.09 (0.03)	0.10 (0.04)	0.14 (0.07)	A	1,28	1.46		AxC	5,140	0.41	
[cm]		EC	0.06 (0.01)	0.24 (0.14)	0.09 (0.03)	0.10 (0.05)	0.11 (0.03)	0.14 (0.06)	E	1,28	20.66	***	ExC	5,140	14.67	***
	Elderly	EO	0.06 (0.02)	0.18 (0.07)	0.13 (0.07)	0.12 (0.04)	0.14 (0.05)	0.14 (0.05)	ExA	1,28	0.01		ExCxA	5,140	1.48	
		EC	0.07 (0.02)	0.28 (0.13)	0.09 (0.02)	0.13 (0.04)	0.12 (0.05)	0.16 (0.05)	C	5,140	47.93	***				
RMS AP	Young	EO	0.12 (0.07)	0.11 (0.05)	0.08 (0.03)	0.10 (0.04)	0.09 (0.04)	0.09 (0.04)	A	1,26	0.74		AxC	5,130	0.99	
[cm]		EC	0.13 (0.05)	0.11 (0.04)	0.08 (0.03)	0.10 (0.04)	0.09 (0.04)	0.09 (0.03)	E	1,26	0.01		ExC	5,130	0.64	
	Elderly	EO	0.13 (0.08)	0.14 (0.08)	0.10 (0.08)	0.09 (0.04)	0.12 (0.11)	0.11 (0.08)	ExA	1,26	0.09		ExCxA	5,130	0.71	
		EC	0.12 (0.07)	0.13 (0.08)	0.08 (0.05)	0.10 (0.06)	0.09 (0.07)	0.12 (0.11)	C	5,130	8.12	***				
MV	Young	EO	1.17 (0.2)	1.36 (0.3)	1.13 (0.3)	1.18 (0.3)	1.11 (0.2)	1.19 (0.3)	A	1,28	0.68		AxC	5,140	0.18	
[cm/s]		EC	1.18 (0.2)	1.38 (0.3)	1.12 (0.3)	1.15 (0.3)	1.12 (0.2)	1.19 (0.3)	E	1,28	4.84	*	ExC	5,140	2.20	
	Elderly	EO	1.11 (0.2)	1.20 (0.2)	1.09 (0.2)	1.07 (0.2)	1.07 (0.2)	1.13 (0.3)	ExA	1,28	4.10		ExCxA	5,140	1.52	
		EC	1.09 (0.2)	1.40 (0.4)	1.10 (0.2)	1.10 (0.2)	1.08 (0.1)	1.15 (0.2)	C	5,140	13.31	***				
Ds	Young	EO	1.28 (0.6)	4.73 (4.6)	1.19 (0.9)	1.10 (0.8)	2.28 (2.1)	1.93 (2.3)	A	1,24	1.85		AxC	5,120	2.75	*
[mm²/s]		EC	1.23 (0.8)	5.74 (2.7)	1.06 (0.7)	1.54 (0.8)	2.54 (2.3)	1.77 (1.2)	E	1,24	17.01	***	ExC	5,120	8.62	***
	Elderly	EO	0.99 (0.6)	4.76 (3.8)	1.27 (1.0)	1.59 (0.9)	1.84 (1.8)	1.87 (1.6)	ExA	1,24	3.11		ExCxA	5,120	1,66	
		EC	1.15 (0.7)	14.78 (16.9)	1.82 (1.6)	1.55 (0.8)	3.48 (3.9)	2.02 (1.9)	C	5,120	22.12	***				
CPs	Young	EO	0.67 (0.6)	1.14 (0.5)	0.65 (0.6)	0.78 (1.1)	0.96 (0.6)	0.95 (0.9)	A	1,10	0.45		AxC	5,50	0.79	
[s]		EC	1.03 (1.4)	1.26 (0.4)	0.86 (0.5)	0.55 (0.8)	0.82 (0.4)	0.64 (1.0)	E	1,10	0.03		ExC	5,50	0.72	
	Elderly	EO	0.83 (1.0)	1.09 (0.6)	1.15 (1.1)	0.43 (0.8)	0.77 (0.9)	0.83 (0.5)	ExA	1,10	0.02		ExCxA	5,50	0.45	
		EC	1.21 (1.4)	1.47 (0.9)	0.92 (1.2)	0.67 (0.4)	1.99 (2.1)	0.88 (1.1)	C	5,50	1.55					
CPmm²	Young	EO	1.36 (1.2)	6.19 (7.8)	0.94 (1.0)	1.11 (1.2)	3.03 (3.1)	1.75 (1.7)	A	1,24	0.28		AxC	5,120	0.24	
[mm²]		EC	2.34 (3.1)	13.91 (16.2)	1.04 (1.0)	0.74 (0.9)	2.29 (2.2)	1.72 (1.1)	E	1,24	23.76	***	ExC	5,120	12.84	***
	Elderly	EO	0.79 (0.6)	5.60 (4.4)	1.63 (2.0)	0.94 (1.1)	2.20 (2.3)	2.15 (3.2)	ExA	1,24	1.81		ExCxA	5,120	1.39	
		EC	1.35 (0.8)	14.92 (11.4)	1.77 (1.3)	1.75 (1.6)	6.01 (4.8)	1.13 (2.6)	C	5,120	20.09	***				
Dl	Young	EO	0.27 (0.4)	0.53 (0.6)	0.23 (0.2)	0.33 (0.3)	0.49 (0.4)	0.24 (0.2)	A	1,26	1.21		AxC	5,130	0.60	
[mm²/s]		EC	0.38 (0.3)	0.40 (1.2)	0.22 (0.2)	0.43 (0.4)	0.59 (0.6)	0.27 (0.2)	E	1,26	1.56		ExC	5,130	0.64	
	Elderly	EO	0.43 (0.5)	0.80 (0.7)	0.52 (0.6)	0.37 (0.3)	0.47 (0.3)	0.34 (0.3)	ExA	1,26	0.55		ExCxA	5,130	0.79	
		EC	0.34 (0.3)	1.20 (2.4)	0.34 (0.4)	0.33 (0.2)	1.14 (1.3)	0.68 (0.7)	C	5,130	3.99	**				
Mean pen force	Young	EO	_	_	0.53 (0.2)	0.53 (0.2)	0.42 (0.1)	0.45 (0.1)	A	1,28	1.07		AxC	3,84	3.26	*
[N]		EC			0.55 (0.1)	0.55 (0.1)	0.43 (0.1)	0.45 (0.1)	E	1,28	0.009		ExC	3,84	0.17	
	Elderly	EO	_	_	0.46 (0.2)	0.45 (0.2)	0.50 (0.2)	0.42 (0.2)	ExA	1,28	1.19		ExCxA	3,84	0.01	
		EC			0.44 (0.1)	0.45 (0.2)	0.48 (0.2)	0.39 (0.2)	C	3,84	2.69					
Area pen	Young	EO	_	_	_	_	9.48 (15.9)	26.99 (27.1)	A	1,28	0.23		AxC	1,28	0.16	
[mm²]		EC					17.07 (20.4)	43.95 (39.9)	E	1,28	2.97		ExC	1,28	4.78	*
	Elderly	EO	_	_	_	_	18.67 (18.8)	35.07 (28.7)	ExA	1,28	1.85		ExCxA	1,28	0.55	
		EC					10.60 (15.4)	46.05 (34.6)	C	1,28	26.96	***				
RMS pen ML	Young	EO	_	_	_	_	1.70 (0.8)	2.71 (1.6)	A	1,28	3.32		AxC	1,28	2.26	
[mm]		EC					1.70 (0.8)	2.49 (1.0)	E	1,28	0.54		ExC	1,28	0.31	
	Elderly	EO	_	_	_	_	2.17 (1.1)	3.37 (1.7)	ExA	1,28	0.01		ExCxA	1,28	1.47	
		EC					1.73 (0.6)	3.52 (1.4)	C	1,28	37.19	***				
RMS pen AP	Young	EO	_	_	_	_	1.69 (1.2)	3.20 (1.6)	A	1,28	0.81		AxC	1,28	2.35	
[mm]		EC					2.00 (1.2)	3.12 (2.0)	E	1,28	1.45		ExC	1,28	0.001	
	Elderly	EO	_	_	_	_	1.77 (1.0)	3.80 (3.3)	ExA	1,28	0.42		ExCxA	1,28	0.67	
		EC					1.98 (1.7)	4.37 (1.9)	C	1,28	35.60	***				

*Note. Mean values (standard deviation in brackets); * p < 0.05, ** p < 0.01, *** p < 0.001;*
Main Effects: A = Age, E = Eyes, C = Condition; Interaction Effects: ExA = Eyes x Age, AxC = Age x Condition, ExC = Eyes x Condition, ExCxA = Eyes x Condition x Age

5.4.1. Effects of the rocker board on postural control in young and older adults

In the SIT condition (i.e., sitting on the rocker board), RMS in the ML direction (Figure 19) and MV were significantly larger than in the quiet-sitting (QS) condition. In contrast, RMS in the AP direction was not affected by the rocker board. In the stabilogram diffusion analysis, Ds (Figure 20), Dl and CPmm² were significantly larger in the rocker-board than in the quiet-sitting condition. Differences between the two age groups were negligible. Only Ds (Figure 20) was reliably larger in the older participants than the young ones in the rocker-board condition, but not in quiet sitting.

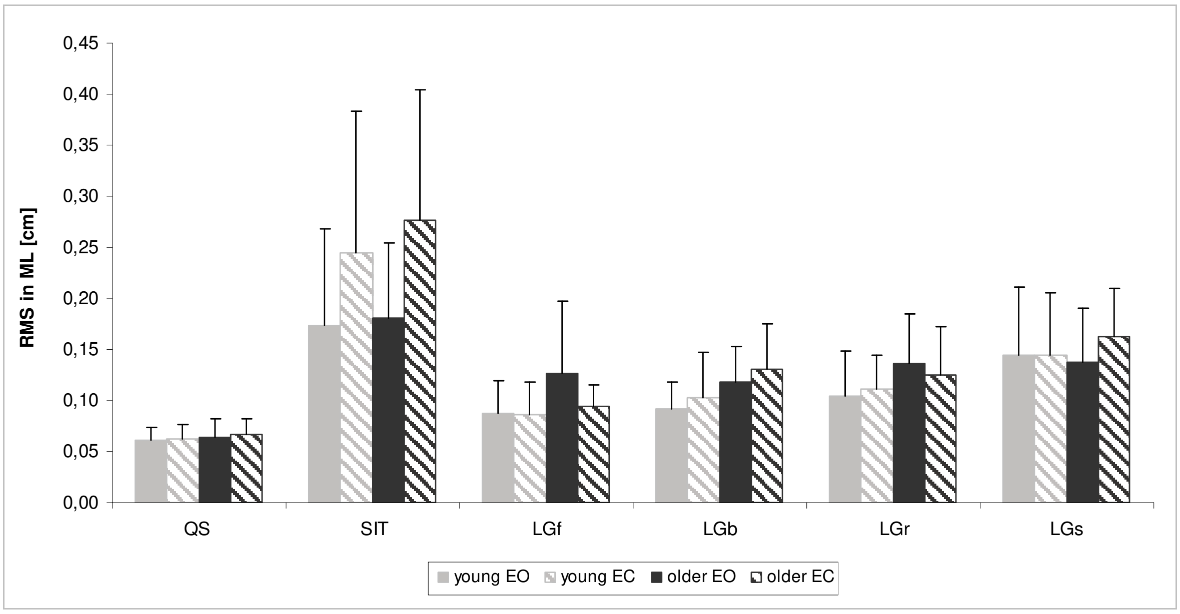

Figure 19: RMS of the COP in the ML direction that is, in the most unstable plane, for young and older participants with EO and EC in six conditions (mean and standard deviation)

5.4.2. Effects of visual deprivation on postural control in young and older adults

The destabilizing effect of visual deprivation was observed in the rocker-board condition, as contrasted with all other conditions, with respect to RMS in the ML direction (Figure 19). In contrast, RMS in the AP direction was not affected by visual deprivation. MV was significantly, though only slightly, higher when vision was withdrawn than in conditions with vision. In the stabilogram diffusion analysis, Ds (Figure 20) and CPmm² were significantly increased by visual deprivation only in the rocker-board condition. Notably, the effect of visual deprivation in particular in the rocker-board condition was not reliably stronger in the older than in the young participants for any of the dependent variables. Although the short-term diffusion coefficient for older adults in the rocker-board condition with EC was markedly higher than all other means (cf. Figure 20), this difference failed to reach statistical significance.

5.4.3. Effects of haptic supplementation on postural control in young and older adults

As compared to the rocker-board condition, haptic supplementation delivered via a fixed or mobile support (LGf, LGb, LGr and LGs) significantly reduced RMS in the ML (Figure 19) and AP directions. MV also significantly decreased with haptic supplementation (LGf, LGb, LGr and LGs). Indeed, it decreased down to the level of the quiet-sitting reference condition, that is, haptic supplementation fully compensated the destabilizing effect of the rocker board. In the stabilogram diffusion analysis, Ds (Figure 20) and $CPmm^2$ were significantly reduced in all four conditions of haptic supplementation (LGf, LGb, LGr and LGs) as compared to the rocker-board condition. Dl was also significantly lower in three conditions of haptic supplementation (LGf, LGb and LGs) than in the rocker-board condition. However, in spite of the reduction relative to the rocker-board condition, the means of Ds (Figure 20), Dl and $CPmm^2$ observed in the four conditions of haptic supplementation remained different from those observed in the quiet-sitting condition. No differences between the two age groups were found even though older participants showed significantly lower cutaneous sensitivity at the fingertip. Accordingly, the effect of haptic supplementation was the same for young and older adults.

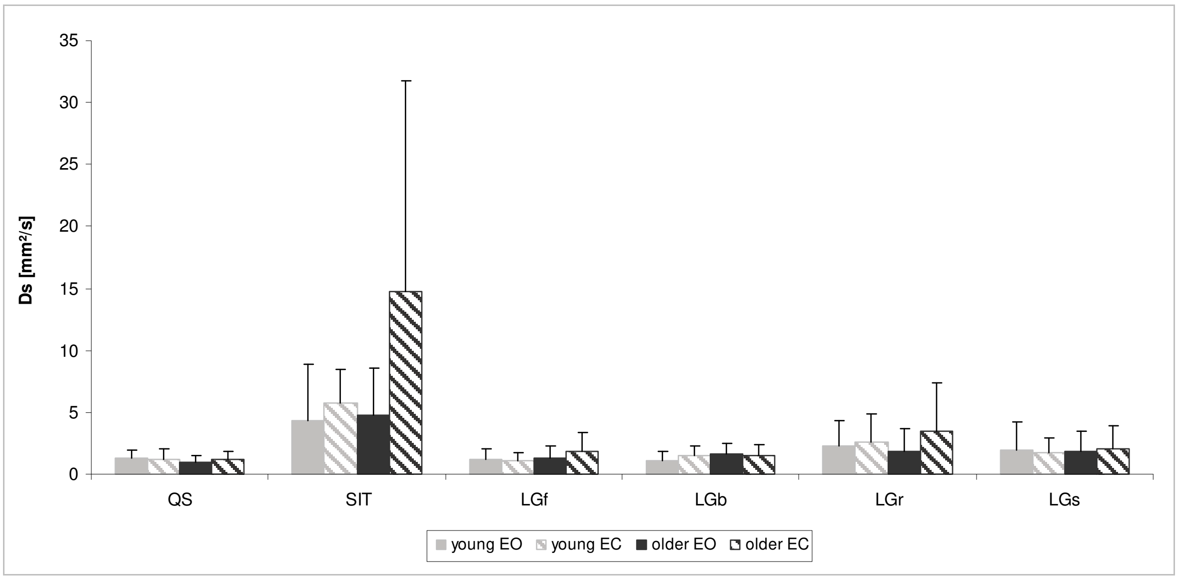

Figure 20: Ds for young and older participants with EO and EC in six conditions (mean and standard deviation)

5.4.4. Variation of haptic cues across different support conditions

Young participants tended (P=0.06) to apply smaller mean force of the pen in the rough-surface (LGr) condition than in the fixed-support (LGf) and the blocked-support (LGb) conditions, whereas, in the older participants, the force applied with the pen did not vary across the different conditions of haptic supplementation. The area of pen displacement was significantly larger in the slippery-surface (LGs) condition than in the rough-surface condition. Similarly, the variability of pen displacements in the ML and AP directions was significantly larger in the slippery-surface condition than in the rough-surface condition. Finally, visual deprivation led to a significant increase in the area of pen displacement in the slippery-surface condition.

5.5. Discussion

The present study aimed to test whether haptic supplementation is suited to improve postural stability during unstable sitting and to compensate for age-related postural instability and the destabilization induced by visual deprivation. In addition, we were interested in identifying the postural control mechanisms (open-loop or closed-loop) that mediate the benefits of haptic supplementation. Against our expectations, there was no generalized effect of age on postural stability in the present study. However, overall, we found a remarkable benefit of haptic supplementation, which largely compensated the effects of visual deprivation and aging, and almost even the destabilization by the rocker board. In the following, we discuss the findings in some detail.

5.5.1. Effects of the rocker board on postural control in young and older adults

As expected, the rocker board perturbed postural stability. Specifically, variability of the COP positions in ML, but not in the AP direction, and mean velocity of the COP were larger than in quiet sitting on a stable base. Moreover, higher short-term and long-term diffusion coefficients were observed during the challenging task when compared to the quiet-sitting condition (see [Cholewicki et al., 2000, Silfies et al., 2003], for comparable results). These results indicate higher open-loop and closed-loop stochastic activity of the COP, respectively. Such increase suggested stronger muscle activation to achieve the challenging task going along with increased noise-like fluctuations in the motor output [Joyce and Rack, 1974].

The increase in critical mean squared displacement in the rocker-board condition (relative to the quiet-sitting condition) suggested that the COP drifts further away from its equilibrium point during open-loop control when the system is challenged by the instability of the rocker board. Critical time intervals, however, were not affected, but remained in a range around 1s in both the quiet-sitting and the rocker-board condition. This suggested that open-loop and closed-loop control mechanisms during sitting operate with the same delays, no matter whether the stability of the system is challenged or not.

5.5.2. Effects of visual deprivation on postural control in young and older adults

In the absence of vision, instability was amplified in the rocker-board condition as reflected by a classical COP variable, the RMS in the ML direction, and by parameters of the SDA (Ds and CPmm²). However, the MV was higher in all conditions, and not only in the rocker-board condition, when vision was withdrawn. These effects of visual deprivation on postural control in challenging tasks are consistent with those observed by Silfies et al. (2003) in an unstable sitting task (seat on a hemisphere). Silfies et al. (2003) suggested that sitting posture is controlled, at least in part, by means of visual cues and that the proprioceptive and vestibular systems do not fully compensate for visual deprivation.

In the present study, older participants were not more affected by visual deprivation than young participants. Such an age-related effect of visual deprivation could have been expected because, in upright standing, older adults have been shown to depend more on vision than young adults [Simoneau et al., 1999]. The absence of such an age-related effect in our study might be specific to the sitting task and perhaps to particular experimental conditions.

5.5.3. Effects of haptic supplementation on postural control in young and older adults

The instability provoked by the rocker board was strongly attenuated by haptic supplementation in both age groups. Furthermore, even withdrawal of visual information was compensated by haptic supplementation. These results suggested that the CNS effectively reweights the available sensory cues provided by multiple sensory systems (haptic, visual, proprioceptive and vestibular) in order to achieve intervertebral and trunk postural adjustments. More importantly, under certain conditions haptic cues from cutaneous mechanoreceptors and muscle spindles of the fingers and arm, that are not commonly relevant for postural control, come to play a functional role in the postural control of sitting. In order to preserve postural stability when another (commonly used) sensory source is withdrawn (here: vision), the function of haptic cues actually becomes comparable to that of the lacking sensory source. Thus, haptic cues improve sitting postural control even though the biomechanical system (spine) involved in the task is highly complex and usually is controlled predominantly on the basis of spinal proprioception [Reeves et al., 2007].

Haptic supplementation produced the same benefits for young and older participants. Thus, the capacity for sensory reweighting is preserved at old age [Allison et al., 2006]. Furthermore, the higher open-loop stochastic activity of the COP observed in older participants in the rocker-board condition was compensated when haptic supplementation was provided. Such compensation of the age-related changes in open-loop postural control mechanisms by haptic supplementation has been shown in the second study of this work on upright standing [Albertsen et al., 2012]. In the framework of the SDA, these results suggested that haptic supplementation helps to reduce steady-state muscle activity and trunk stiffness during sitting. Without the additional sensory cues, stiffening of the trunk is part of the strategy of older adults to master the challenging postural task ([Collins et al., 1995], for consistent interpretation).

It is remarkable that older participants benefited to the same extent as young participants from haptic supplementation even though clinical tests of cutaneous sensitivity showed an age-related decline of spatial acuity at the fingertip (young: 2.8 mm, elderly: 3.8 mm). Poorer spatial acuity presumably results from changes in innervation density of slow- and fast-adapting mechanoreceptors of the fingertip ([Tremblay et al., 2005], young: ~1 mm, elderly: ~2.5 mm). In the present study, spatial acuity was reduced at older age, but not yet pathological (fair: > 6 mm, poor: > 11mm, Touch-Test® Two-Point Discriminator). According to these results, the age-related decline in spatial acuity does not suspend older adults from the benefits of haptic supplementation [Tremblay et al., 2004]. The benefits most likely originate at a central rather than a peripheral level of the nervous system.

5.5.4. Variation of haptic cues across different support conditions

Haptic supplementation improved postural stability independent of the stability of the pen support (fixed or mobile). These results are consistent with those of previous studies presented in the present work on upright standing (studies I and II [Albertsen et al., 2010, Albertsen et al., 2012], respectively). They strongly suggested that the haptic information, which is provided by the mechanoreceptors of the fingers and the arm, is used to improve postural control even in the absence of a fixed support. Rather than a fixed support, it seems critical that the haptic information relates to the body sway of the sitting person. This interpretation contrasts with those proposed in earlier light-touch studies using a fixed support [Jeka and Lackner, 1994, Jeka and Lackner, 1995, Holden et al., 1994, Tremblay et al., 2004]. There it was claimed that a fixed point in the environment provides a frame of reference for spatial orientation and therefore is critical for the beneficial effects of haptic supplementation.

Although the rocker board in the present study destabilized sitting only in the ML direction, the variability of the pen displacements was of the same magnitude in the ML (unstable plane) and AP directions (stable plane). Most likely, the pen displacements in both directions were functional with respect to postural control, as we observed effects of haptic supplementation on COP variability in both the AP and ML directions. In our previous studies (I and II) on upright standing [Albertsen et al., 2010, Albertsen et al., 2012], and in contrast to the present study, the lightly touching arm was strapped to the trunk. In mobile-support conditions, this led to sway-related stick movements only in the AP direction (unstable plane), and a gain in stability during upright stance was exclusively observed in this direction. These results suggested that the effect of haptic supplementation is limited to those planes, in which variations of contact force and proprioception are related to body sway [Albertsen et al., 2010]. In the present study, this was the case for pen movements both in the ML and AP directions. Thus, even though the rocker board predominantly destabilized sitting posture in the ML direction, body oscillations in the AP direction that led to pen displacements and haptic variations in this direction also served to improve stability.

5.5.5. Effects of haptic cues on open-loop and closed-loop postural control mechanisms in young and older adults

The results of the SDA extend previous results on the influence of haptic supplementation on open-loop and closed-loop postural control during upright standing [Albertsen et al., 2012] to sitting. For most parameters of the SDA, the effect of haptic supplementation was independent of whether the pen support was fixed or mobile. The smaller long-term diffusion coefficients in conditions of haptic supplementation (with the exception of the condition LGr) suggested that closed-loop stochastic activity is reduced thanks to additional sensory cues. Comparable results have been reported by Riley et al. (1997) for haptic cues during upright standing and by Silfies et al. (2003) for visual cues during unstable sitting. The present findings confirmed the impact of haptic supplementation on closed-loop control of unstable sitting.

In addition to closed-loop control, open-loop control was also affected by haptic supplementation. The smaller critical mean squared displacement and short-term diffusion coefficient in conditions of haptic supplementation suggested a reduced open-loop stochastic activity. This observation is consistent with findings of Sullivan et al. (2009) on upright standing, who observed a smaller open-loop stochastic activity in older adults as a consequence of sensory supplementation (such as touch or vision) (see [Riley et al., 1997], for comparable results). The only study on unstable sitting, that produced comparable results, supplemented participants with additional visual rather than haptic cues [Silfies et al., 2003]. In line with Collins and colleagues [Collins and De Luca, 1993, Collins et al., 1995], these findings indicate a decline of steady-state muscle activity in the presence of haptic cues and, thus, reduced noise-like fluctuations in the motor output [Joyce and Rack, 1974]. Consistent with this interpretation, Jeka and Lackner (1995) observed reduced myoelectric activity of postural muscles (~40-50%) during upright standing when participants lightly touched a fixed support as compared to conditions without touch.

5.6. Conclusion

In the present study, we demonstrated an impact of haptic supplementation on both open-loop and closed-loop mechanisms of postural control of upright sitting in young and older adults. In older adults the benefits of haptic supplementation were observed in spite of their reduced cutaneous sensitivity. Most likely, in both age groups, a less diffusive, more stable COP due to haptic supplementation in the short-term range reduces the need for corrective COP modulations in the long-term range (see [Collins and De Luca, 1993]). When put into perspective with corresponding observations on the control of upright standing, the results of the present study strengthen the notion of commonalities of the mechanisms involved in the postural control of standing and sitting in spite of the different complex biomechanical systems involved in the two postural tasks. In view of potential future applications towards portable haptic assistive devices, it still remained to explore the effect of haptic cues from a mobile stick in dynamic situation that is, in situations where the postural control system is challenged.

6. Study IV: Dynamic rocker-board stance

6.1. Introduction

After having demonstrated the effect of sway-related haptic cues from a mobile stick during quiet upright stance and perturbed sitting, we explored their effect on perturbed upright stance, especially, on coordinative patterns between the lower and the upper body. Successful postural control during perturbed upright stance might require coordinated control of several body components [Kiemel et al., 2008, Ting, 2007]. Thus, in the present experiment, our analysis on the influence of haptic supplementation on coordinative patterns between the different body segments was based on the model of a two-link inverted pendulum (ankle and hip).

Some studies already tested the effect of a LT on postural stability of young participants standing on a rocker board (1 DoF in the AP direction, [Kazennikov et al., 2005, Kazennikov et al., 2008, Hausbeck et al., 2009]). These studies used fixed or mobile light-touch supports (i.e., a classical fixed support, small loads held in front of the body or lightly-touched canes) to provide haptic supplementation. The study by Hausbeck et al. (2009) was the only one comparing canes of three different stabilities (horizontally-held cane, rocker cane, quad cane) that provided sensory cues during rocker-board stance in a perturbing visual environment. The authors found that the perturbation induced by the visual environment (which caused an increase in COM and angular displacements of ankle and hip) could be compensated by haptic cues from more or less stable cane-supports. These results suggested that the CNS can disregard unreliable visual information due to additional orientation cues provided by a cane in order to improve the control of different body segments during rocker-board stance. The results by Kazennikov et al. (2008) suggested that additional orientation cues can be used by the CNS to better control the perturbed posture on a rocker board. The authors showed that holding a 1000-g-load reduced the sway of the rocker board controlled by the participants. The same authors observed in an earlier study a less destabilizing effect of calf muscle vibration when a LT on a fixed rail was simultaneously performed [Kazennikov et al., 2005]. This gain in stability through the LT was more pronounced when the platform underneath the rocker board was stationary than when it moved very slowly back- and forward. The authors concluded that the reliability of the haptic cues determines whether or not they can be used to build a reference frame for postural control. In this perspective, they hypothesized that haptic cues from a sliding finger are less appropriate to build such reference frame and thereby lead to a reduced stabilizing effect.

In summary, these studies suggested that haptic cues (inertial forces by holding an object in the hand or haptic cues by lightly touching a fixed support) provided during rocker-board stance can be integrated by the CNS. Consequently, due to additional haptic cues postural control can be improved, which results in reduced COP sway and angular displacement of body segments or the rocker board that participants are standing on. The availability of sway-related haptic cues changes the contribution of sensory cues to postural control in favor of proprioceptive and cutaneous cues.

However, in view of the transfer of useful haptic cues to everyday-life posture and locomotion, a "limitation" of all these studies was that they did not vary haptic cues delivered from a support that entirely moved with the participants (except haptic cues delivered by a load that was not in contact with the ground as would be expected by a cane-like device). According to Newell (1986)'s model, they manipulated mainly the task-inherent constraints of postural control (perturbed stance).

In contrast, the mobile-stick experimental paradigm that was applied to a rocker-board stance in the present study aimed to manipulate both task-inherent (perturbed stance) and environmental (sensory cues) factors while testing young participants. It is of theoretical interest to investigate if the effect of a LG of a mobile stick persists, when the user is perturbed. More precisely, it is unknown if the postural control system can deal with the potential cognitive effort needed for sensory transformations of haptic cues from a mobile stick to a common reference frame when the system is challenged. Not only no fixed reference point is provided to the user by the mobile stick but even more, the postural control system is challenged, which might preclude that the CNS can make use of the haptic cues in this specific task. On the other hand, it could be that the enhanced sway-related stick movements in the present rocker-board task amplify orientation cues available to the CNS that can thereby improve postural stability.

Concerning the effect of a LT on kinematics of the lower and the upper body, few authors observed decreased variability of both body segments (lower and upper body) due to haptic supplementation during quiet [Zhang et al., 2007] and during perturbed upright stance [Hausbeck et al., 2009]. Moreover, owing to the spectral analysis of inter-segment body motion, results by Zhang et al. (2007) suggested that in-phase (< 1 Hz) and anti-phase (> 1 Hz) patterns between segments co-exist even during unperturbed stance (see also [Creath et al., 2005]). In addition, the authors suggested that the in-phase pattern is more influenced by the LT on a fixed support than the anti-phase pattern (transition from in-phase to anti-phase at a lower sway frequency). The authors concluded that the in-phase pattern is presumably under higher amount of neural control and therefore sensitive to haptic supplementation, in contrast to the anti-phase pattern that rather emerges due to the plant dynamics. To our knowledge, however, any study investigated the influence of a LG of a mobile stick on coordinative patterns between the leg and trunk segments during rocker-board stance. As coordinative patterns between the lower and the upper body might change when standing on the rocker board, it remained to explore if haptic cues from a mobile stick could stabilize posture by compensating for these behavioral changes. Two possible changes when standing on the rocker board could be imagined. If the rocker board only slightly challenged the postural control system, it might choose an in-phase pattern between the two segments that corresponds to positively-correlated segments [Almeida et al., 2006]. If the rocker board was sufficiently challenging, an anti-phase pattern might emerge that corresponds to negatively-correlated segments [Kiemel et al., 2008, Ting, 2007].

6.2. Aims and hypotheses

First of all, we expected that postural stability during upright stance on the rocker board is reduced and that coordinative patterns between the leg and trunk segments change. Second, we expected that sway-related haptic cues improve postural stability during perturbed standing on the rocker board. This should be the case even in the mobile-support conditions, where the arm-stick system was more complex than in studies I and II. As, in these conditions 1) the arms were not strapped to the body, 2) the stick was free to move on the ground and 3) the entire body was perturbed, the LG does not provide a fixed spatial referent but presumably sway-related cues from the movements of the stick on the ground.

Finally, we hypothesized that haptic cues can be integrated by the CNS and serve to compensate for changes in coordinative patterns of different body segments when perturbed.

6.3. Materials and methods

6.3.1. Participants

Eight young participants (3 women and 5 men, mean age 25.8 ± 2.1 years) took voluntarily part in the experiment. They were right-handed, physically active and had no self-declared musculoskeletal injuries, or perceptive, cognitive and motor disorders that might affect their ability to maintain balance or to understand task instructions. The experimental protocol was presented to all participants, which gave a written consent before undergoing the experiment. The protocol was approved by a local ethics committee and has therefore been in accordance with the ethical standards laid down in the declaration of Helsinki.

6.3.2. Task and experimental design

Six experimental conditions were tested with EO (Figure 21): 1) quiet stance (QS), 2) rocker-board stance (STANCE) and four conditions of haptic supplementation (a fixed-support and three mobile-support conditions). During QS, participants stood directly in the center of the force platform. During the STANCE condition, participants stood in the center of a rocker board that was positioned on top of a force platform. The rocker board destabilized participants in the AP direction. Haptic supplementation was provided through the LG of a stick with the left hand (chapter 2.4.1.). All conditions of haptic supplementation were tested on the rocker board with the stick orientated in the plane of greatest instability that is, in the AP direction. The mobility of the stick and its resistance offered against body oscillations were manipulated in four conditions of haptic supplementation: 3) a fixed- (LGf), 4) a blocked-support condition (LGb), 5) a slippery- (LGs) and 6) a rough-surface condition (LGr).

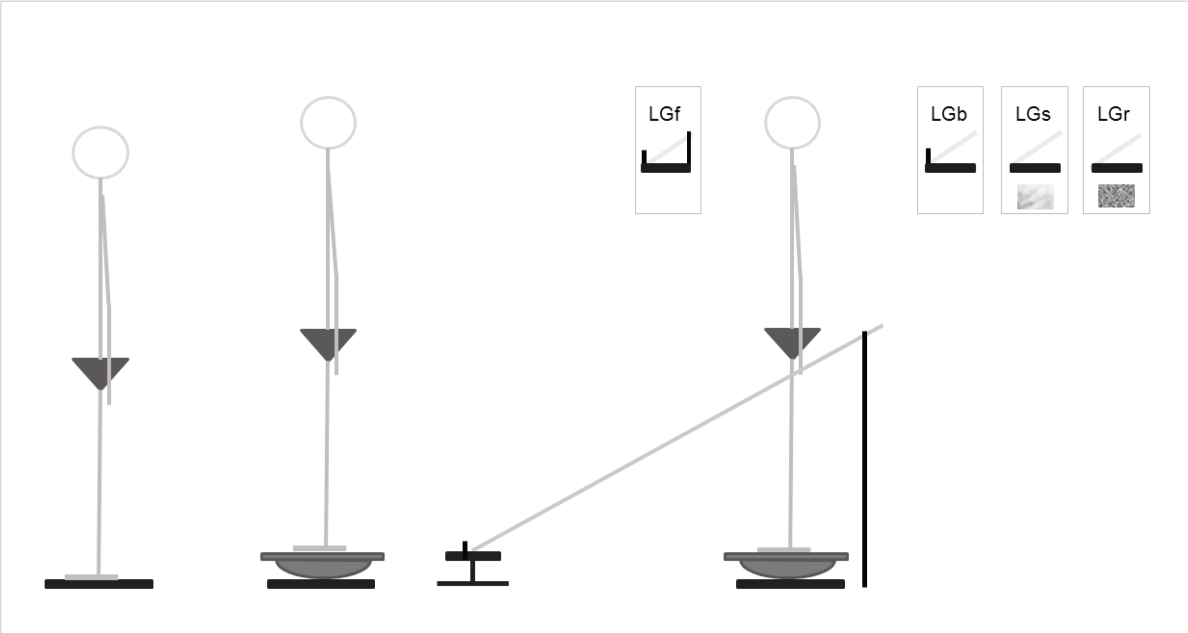

Figure 21: Six experimental conditions of study IV (see Figure 12 left, for grip details)

In all conditions, participants were asked to maintain a natural erect standing posture with both arms held straight along the body. The feet of the participants were placed at hip-width, side-by-side and the toeholds were positioned in a distance of 20 cm, in an angle of 30°. They were asked to fixate a point in eye height at 1.5 m on a wall. In all conditions, the left hand was to be held short behind a reflexive marker at the hip (chapter 6.3.3.). The stick was always out of sight of participants.

Participants did four trials of 45 s in each condition. Breaks lasted 30 s between trials and 60 s between conditions. Each trial started when participants were able to stand quietly without exceeding the force threshold (< 1.6 N). The total experimental session lasted about 1 hour.

6.3.3. Apparatus and measures

A rocker board (40 cm x 40 cm of 1.1 cm thick Plexiglas®, bearing surface in 4.4 cm height, 53.5 cm radius of segment of circle, 1 DoF in the AP direction) was placed on a force platform (AMTI, Advanced Mechanical Technology, Inc., MA, USA) that measured the three components of the resultant ground reaction force to determine the COP trajectories. Kinematic data were recorded by means of a 6-camera 3D motion capture system (Vicon 624 Workstation, MCam2, software version 4.6, Oxford Metrics, UK). Reflective markers, placed at specific anatomic landmarks (ankle: lateral malleolus, hip: superior aspect of greater trochanter and shoulder: acromioclavicular joint) and on the rocker board (front left and back left), were used to determine sagittal-plane kinematics of the leg (ankle and hip) and trunk segments (hip and shoulder) and of the rocker board with respect to vertical (0°, anti-clockwise). COP data in the AP direction and sagittal-plane kinematic data were sampled at 100 Hz. They were collected on a PC and analyzed offline with the help of Matlab 7.0 (The MathWork®, Inc., Natrick, MA, USA). The first 3 secs of the COP and kinematic data were neglected and 42 s of the sampled data were analyzed. Only COP data were low-pass filtered (second-order Butterworth, 10 Hz, dual-pass).

Based on COP trajectories, four dependent variables were calculated for each trial: 1) RMS [cm], 2) MV [cm/s], 3) MPF [Hz] and 4) MTP [mm²] (see chapter 1.1.2.). Based on the trajectories of the angular displacements of the leg and trunk segments and the rocker board, three dependent variables were calculated for each trial: 5) the weighted range (w. Range) [°], 6) the MPF [Hz] and 7) the MTP [deg²]. The weighted range was calculated by subtracting the mean of the greatest values from the mean of the lowest values of the angular displacements of each segment that were weighted by considering the number of data points constituting each positive or negative peak (adapted from [Hausbeck et al., 2009]). Individual data of the COP and kinematics were averaged across the trials of each condition and used to carry out 6-conditions repeated-measure ANOVAs.

Cross-correlations between the leg and trunk segments were calculated in order to determine, at which time lag (lag [ms]) the two body segments were most strongly correlated (cross-correlation coefficient (CorrLT)). Cross-correlations were performed at each of 150 steps (10 ms/ step) in both the forward and backward directions from zero lag. Cross-correlation coefficients were submitted to an Arcsine transformation [Abdi, 1987]. First, a t-test was carried out between the two conditions QS and STANCE. Thereafter 5-conditions repeated-measure ANOVA were carried out between the STANCE condition and all conditions of haptic supplementation (LGf, LGb, LGr and LGs). Normality was checked by means of Kolmogorov-Smirnov tests. Significant effects were further analyzed using Newman-Keuls post-hoc test (threshold of significance at *P*=0.05).

6.4. Results

In the following, we present the effects of the rocker board on postural stability of young participants. Thereafter the effects of the fixed- and mobile-support conditions on postural stability are described. Finally, we present the results concerning the cross-correlation between the leg and trunk segments. A summary of results is given in Tables 4 (mean, standard deviation, F- and p-values). Even though the results of the post-hoc tests are not presented in detail, the differences between experimental conditions that are described below were significant or showed a trend (*P*=0.06).

6.4.1. Effects of the rocker board on postural control

In the STANCE condition (i.e., standing on the rocker board) the RMS and the MTP of the COP were significantly larger than in the QS condition. In addition, the MV of the COP was significantly larger at lower MPF in the STANCE than in the QS condition. In the kinematic analysis, the weighted range of the leg and trunk angular displacements were significantly higher in the STANCE than in the QS condition. Similarly, the MTP of the leg and trunk angular displacements was significantly higher when standing on the rocker board than in the QS condition. These results were a prerequisite to analyze the effect of haptic supplementation.

6.4.2. Effects of the fixed-support condition on postural control

As compared to the STANCE condition, haptic supplementation provided by a fixed support significantly reduced the RMS, the MV and the MTP of the COP. In the kinematic analysis, the weighted range and the MTP of the leg, trunk and rocker-board angular displacements were significantly reduced. In contrast, only the MPF of the rocker-board angular displacements and the MPF of the COP were significantly higher due to this type of haptic supplementation than in the STANCE condition. The MPF of the leg and trunk angular displacements were not affect by haptic supplementation of a fixed support.

6.4.3. Effects of the mobile-support conditions on postural control

As compared to the STANCE condition and similar to the effect of haptic supplementation from a fixed support, haptic supplementation provided by mobile supports (LGb and LGr) significantly reduced the RMS, MV and MTP of the COP. In the kinematic analysis, the weighted range and the MTP of the leg, trunk and rocker-board angular displacements were significantly reduced in the mobile-support conditions. In contrast, the MPF of the COP and of the leg, trunk and rocker board were not affected in the two mobile-support conditions. Constituting an exception within the conditions of haptic supplementation, the LGs condition had a less consistent effect throughout variables. In the LGs condition, only the MV and the MTP of the COP were significantly reduced. In contrast, neither the RMS or the MPF of the COP nor the weighted range or the MTP of angular displacements of the leg, trunk and rocker board were influenced.

6.4.4. Cross-correlation between the leg and trunk segments

The analysis of the cross-correlation between the leg and trunk segments (without taking into account their corresponding sign) revealed strong correlations between the two segments in the different conditions (0.56 to 0.66) at relatively constant time lags (363 ms to 488 ms). Most of the trials (90.6% to 100%, Table 5) were positively-correlated, which explained why further analysis only considered the positively-correlated trials.

Table 4: Results summary for variables extracted from the COP trajectories and the angular displacement of the leg and trunk segments and the rocker board

Variable	Condition						F-value	p-value
	QS	STANCE	LGf	LGb	LGr	LGs		
RMS [cm]	0.43 (0.12)	1.14 (0.36)	0.75 (0.22)	0.75 (0.25)	0.79 (0.21)	1.06 (0.27)	F(5,35) = 23.80	***
MV [cm/s]	1.14 (0.39)	1.93 (0.37)	1.52 (0.38)	1.46 (0.30)	1.54 (0.33)	1.69 (0.41)	F(5,35) = 36.02	***
COP MPF [Hz]	0.32 (0.09)	0.25 (0.04)	0.32 (0.07)	0.26 (0.07)	0.26 (0.06)	0.25 (0.07)	F(5,35) = 4.43	**
COP MTP [mm²]	6.93 (5.10)	46.09 (34.79)	19.89 (16.05)	21.30 (14.80)	24.66 (14.99)	33.04 (17.22)	F(5,35) = 9.98	***
Leg w. Range [°]	0.79 (0.32)	1.70 (0.59)	1.05 (0.41)	1.01 (0.29)	1.04 (0.26)	1.56 (0.40)	F(5,35) = 16.66	***
Trunk w. Range [°]	0.12 (0.39)	1.73 (0.47)	1.23 (0.30)	1.32 (0.32)	1.32 (0.44)	1.66 (0.66)	F(5,35) = 6.37	***
Rocker board w. Range [°]	–	3.26 (1.00)	2.10 (0.73)	2.13 (0.70)	2.20 (0.61)	3.04 (0.70)	F(4,28) = 13.38	***
Leg MPF [Hz]	0.19 (0.04)	0.16 (0.01)	0.20 (0.04)	0.18 (0.04)	0.16 (0.03)	0.15 (0.02)	F(5,35) = 3.29	*
Trunk MPF [Hz]	0.19 (0.04)	0.18 (0.03)	0.23 (0.07)	0.22 (0.08)	0.20 (0.01)	0.19 (0.03)	F(5,35) = 1.97	
Rocker board MPF [Hz]	–	0.25 (0.04)	0.32 (0.06)	0.25 (0.06)	0.25 (0.05)	0.24 (0.06)	F(4,28) = 6.04	**
Leg MTP [deg²]	0.02 (0.02)	0.11 (0.10)	0.04 (0.04)	0.04 (0.03)	0.05 (0.03)	0.08 (0.04)	F(5,35) = 6.05	***
Trunk MTP [deg²]	0.05 (0.04)	0.11 (0.05)	0.06 (0.03)	0.07 (0.04)	0.07 (0.05)	0.08 (0.06)	F(5,35) = 4.78	**
Rocker board MTP [deg²]	–	0.43 (0.33)	0.19 (0.16)	0.20 (0.15)	0.23 (0.14)	0.32 (0.16)	F(4,28) = 7.09	***

*Note. Mean values (standard deviation in brackets), * p<0.05, ** p<0.01, ***p<0.001*

First, within the positively-correlated trials, the cross-correlation coefficient in the QS condition was significantly lower than in the STANCE condition (t=-3.71, P<0.05**). No significant difference was found between the time lags in these two conditions. Second, the analysis (F(4,28)=0.45, P>0.05) did not show significant differences between the cross-correlation coefficients nor between the time lags in the five experimental conditions (STANCE, LGf, LGb, LGr and LGs, Table 5).

Table 5: Cross-correlation coefficients between the leg and trunk segments (CorrLT) and corresponding time lags (lag) in different experimental conditions

Variables	Condition					
	QS	STANCE	LGf	LGb	LGr	LGs
CorrLT	0.57 (0.20)	0.65 (0.21)	0.56 (0.25)	0.61 (0.19)	0.62 (0.20)	0.66 (0.17)
lag [ms]	363 (457)	486 (485)	458 (450)	488 (405)	443 (372)	446 (453)
$\%_{pos}$	90.6 %	93.1 %	87.5 %	100%	96.9 %	96.9 %
$CorrLT_{pos}$	0.61 (0.21)	0.76 (0.23)	0.64 (0.21)	0.66 (0.18)	0.70 (0.12)	0.74 (0.17)
lag_{pos} [ms]	301 (199)	462 (366)	446 (319)	490 (312)	416 (201)	407 (337)

Note. Percentage of the positively-correlated trials ($\%_{pos}$), corresponding $CorrLT_{pos}$ and $lag_{pos;}$ (means and standard deviation in brackets)

6.5. Discussion

The present study aimed to test whether haptic supplementation provided by a mobile stick can improve postural stability during rocker–board stance and compensate for changes in the coordinative pattern between the leg and trunk segments due to the destabilization of the rocker board. Results confirmed our main hypothesis about the stabilizing effect of haptic cues from a mobile support when the balancing body is perturbed. In the following, we discuss the findings of this study.

6.5.1. Effects of the rocker board on postural control

As expected, the rocker board increased postural instability. This instability was reflected by higher variability, speed and higher MTP of the COP. In addition, the weighted range and the MTP of the angular displacements of the lower and the upper body increased while standing on the rocker board when compared to the QS condition. These results indicated that the postural control system is challenged on the rocker board, which was a prerequisite to test the effect of haptic supplementation.

The analysis of the cross-correlation between the leg and trunk segments showed a strong correlation in the QS condition between the two segments. Consistent with the literature about postural control during quiet upright stance [Maurer and Peterka, 2005, Peterka, 2000], this suggested an ankle strategy (with a strong in-phase coupling of both body segments) used by participants to maintain upright stance when the system is not challenged.

The rocker board significantly affected this coupling that is, it increased the positive correlation between the two segments even more. In the same way, Almeida et al. (2006) previously observed the use of an ankle strategy by participants while standing on a rocker board. The authors observed a co-activation of posterior and anterior muscles of the legs and trunk and suggested that this co-activation was achieved to increase joint stiffness (of the knee and hip) and to facilitate the balancing task on the rocker board. To corroborate this interpretation, we found increased MTP of the frequency spectrum of the COP and of the leg and trunk segments presumably due to an increase in muscle activity and/ or co-activation of antagonistic lower limb muscles (see [Laughton et al., 2003], quiet upright stance).

6.5.2. Effects of haptic supplementation on postural control

The instability provoked by the rocker board was attenuated by haptic supplementation provided by the fixed- (LGf) and two mobile-support conditions (LGb and LGr). This gain in stability was reflected by a decrease in all COP variables along with a decrease in all variables of the kinematic data. These results are in contrast to results by Hausbeck et al. (2009), in that they did not show a greater stabilizing effect by a LT on a fixed support when compared to a mobile one. They suggested that the CNS can use additional available haptic cues provided by either a fixed or a mobile support to stabilize the COP and the two body segments. Even if an additional cognitive effort was required in order to transform orientation cues provided by a mobile support to a common reference frame for sensory integration, this did not prevent the CNS from taking advantage of these cues.

Furthermore, even without strapping the light-grip arm to the body it appeared that sufficient sway-related haptic cues are provided to the CNS in the mobile-support conditions to improve postural control. Thus, the results suggested that the increased complexity of the stick-arm system does not reduce the stabilizing effect of haptic cues.

As reported in previous studies, it appeared to be crucial for effective postural stabilization that haptic cues are related to body sway and that sufficient resistance is offered against body sway. Under these conditions, the availability of a fixed reference point becomes dispensable. The less consistent stabilizing effect in the slippery-surface condition corroborated the above-mentioned interpretation. Reduced (but not absent) resistance in the slippery-surface condition could explain why the CNS can make use of sway-related haptic cues to better control the COP (reduced speed and MTP) but not to reduce the angular displacements of the body segments. Due to the great mobility of the stick on the slippery surface another alternative explanation for the less consistent effect of haptic cues in the slippery-surface condition could be that more complex sensory transformations are needed to integrate these cues together with other sensory cues [Sozzi et al., 2012]. When comparing these findings (during rocker-board stance) to those of the study I (during quiet stance), there was a difference in the stabilizing effect in the slippery-surface condition. During quiet stance, the slippery-surface condition did not affect the COP, whereas, during rocker-board stance, the slippery-surface condition showed a stabilizing effect. Two possible explanations for the effect of haptic cues provided by the interaction with a slippery surface in the present study can be put forward. The amplified movement of the stick due to the destabilization by the rocker board might have amplified the haptic cues provided by the mobile stick ([Rogers et al., 2001], for a consistent interpretation concerning the efficient effect of a PS applied to high body parts). Alternatively, even small sway-related orientation cues might become functional for postural control when the system is challenged ([Hausbeck et al., 2009], for a consistent interpretation concerning the stabilizing effect of a horizontally-held cane only in a perturbing but not in a stable visual environment).

6.5.3. Cross-correlation between the leg and trunk segments

The present results did not confirm our third hypothesis that haptic cues compensate for changes in coordinative patterns of different body segments when perturbed. In all experimental conditions strong, mainly positive correlations were observed. The rocker board induced a stronger positive correlation between the leg and trunk segments when compared to the QS condition. Even though the positive correlation between body segments on the rocker board appeared to decrease due to haptic supplementation, this difference failed to reach significance. None of the conditions of haptic supplementation significantly affected the correlation between the two body segments when compared to the STANCE condition. These results were against our expectations that we based on findings by Zhang et al. (2007). The authors suggested that the in-phase pattern between segments during quiet upright stance (<1 Hz) is more sensitive to haptic cues than the anti-phase pattern (> 1 Hz). This was explained by the fact that the in-phase pattern is under neural control, whereas the anti-phase pattern emerges due to plant dynamics. As the rocker board in our study induced a strong positive correlation that suggested an in-phase pattern between body segments, we expected the coordinative pattern to be influenced by haptic supplementation. However, we underline that Zhang and colleagues (2007) used the method of spectral analysis of inter-segment body motion to analyze the coordinative pattern at different sway frequencies. In contrast, in the present study, we adopted a classical time-domain analysis of the angular displacements of the segments and did not observe an influence of haptic supplementation on the in-phase pattern adopted by participants on the rocker board. We concluded that the coordinative pattern and so the postural strategy remained the same with or without haptic supplementation. At the same time, the weighted range of angular displacements of the two segments and the COP displacements were reduced due to haptic supplementation, which suggested a better control when additional orientation cues are provided. To our knowledge, this study is the only one to explore the effect of haptic cues from a mobile support on the coordinative pattern between body segments during rocker-board stance.

As mentioned above, the strategy to maintain upright stance on the rocker board in the present study appeared to be an ankle strategy (see [Almeida et al., 2006]), even though a spectral analysis of inter-segment body motion (see [Creath et al., 2005, Zhang et al., 2007]) might have led to different results. Accordingly, in our study, the hip was not used in an anti-phase pattern with the ankle to more effectively control the COM position. This might be due to the fact that the rocker board tested here was not sufficiently challenging to yield changes in coordinative patterns involving two DoFs (ankle and hip). However, the light-grip paradigm obliged us to neglect the possibility of very strong perturbations by the rocker board (that could have provoked anti-phase patterns) as they could also have provoked a firm grip of the participants due to high postural challenge or fear. Accordingly, the rocker board chosen for this study was a reasonable compromise. Further research is needed to test if haptic cues from a mobile support are suited to change the postural strategy when severly perturbed by a rocker board (reverse a perturbation-induced hip strategy to an ankle strategy).

6.6. Conclusion

In summary, haptic supplementation from a fixed or mobile support can be used by the CNS to better control rocker-board stance given that sufficient resistance is offered against body sway. This is the case, even in the absence of a fixed spatial referent. Reduced resistance offered against body sway in the LGs condition leads to a less consistent stabilizing effect. Though angular displacements of segments (and the COP) are reduced when provided with haptic supplementation the coupling between the body segments remains unchanged. It should be explored if this is also the case in conditions of abrupt external perturbations.

7. Study V: Perturbed stance on a sliding platform

7.1. Introduction

The results of the study IV suggested that, during rocker-board stance, haptic cues delivered by a mobile stick change COP and angular displacements of the leg and trunk segments. This results in a reduction of postural oscillations. To a certain extent, even haptic cues arising from the interaction with a low-resistance surface (LGs) showed a stabilizing effect. However, postural perturbation induced by the rocker board resulted from relatively slight continuous rotational movements of the support surface that depended on the body sway of the participants. Accordingly, the question remained of whether the benefit of haptic cues from a mobile support still persisted in situations where participants are suddenly and more severely perturbed. Reactive balance control can be tested applying sudden support-surface translations to the standing participant [Nashner, 1977]. According to Reeves et al. (2007), the term robustness (instead of the term stability) is commonly accepted to refer to the ability of maintaining stable behavior in response to this kind of external perturbation. From Reeves et al. (2007)'s point of view, the term stability exclusively refers to the fact that the body remains in its position or close to it. The system is unstable when the body falls (i.e., the projection of the COM moving significantly outside the BOS). Enhanced robustness of a system to perturbation can be achieved due to the adjustment of different parameters within the postural control system, for example, stiffness and feedback gain.

Time delays are very important when achieving upright stance during sudden support-surface translations. Efficient postural control has to be realized within shortest possible delays to prevent injury or falls. It has been shown that, after a support-surface translation, instantaneous muscle stiffness together with initial automatic muscle activation (functional stretch responses at ~100 ms, postural reflex at ~120 ms) achieve a first postural reaction. Actual feedback-based postural corrections apparent in the body sway occur at around 300 ms [Nashner, 1976]. As suggested by Allison et al. (2006), older adults are able to reweight sensory inputs in order to achieve postural control in slowly changing sensory environments. Horak [Horak et al., 1989, Teasdale et al., 1991] observed that older adults achieve deficient central integration, such as slow sensory processing, during severe (sensory) perturbations. However, the time course of multisensory reweighting is still unclear [Allison et al., 2006]. Therefore, it is even more worth testing whether older adults can make use of haptic cues from a mobile stick to improve the postural response to a sudden external perturbation. The perturbation of upright stance chosen in the present study, sudden backward translations of the support surface, has been formerly found to be sensitive to age- or disease-related differences in postural control [Dickstein et al., 2003, Ghulyan et al., 2005]. Therefore, we considered it as suitable to test if there are age-related differences in the benefit of haptic cues mediated by a mobile stick in response to a sudden support-surface translation.

Only two studies examined the effect of additional haptic cues on reactive balance control. One study tested healthy young adults [Johannsen et al., 2007] and the other compared healthy older participants and older diabetic neuropathy patients [Dickstein et al., 2003]. Dickstein et al. (2003) compared the effect of haptic cues (no touch, light, or heavy touch) on the response latency (initial EMG activation) and the initial COP velocity (within first 75 ms) during sudden support-surface translations. The platform moved backwards at three different velocities (0.01, 0.02 and 0.03 m/s, amplitude 60 mm) and so the response scaling to different platform velocities was studied. Results showed that the LT on a fixed support did not affect the response latency of either group. However, the initial COP velocity in the AP direction decreased with touch and touch improved the response scaling of all participants. More precisely, healthy older controls could benefit from a LT and older patients only from heavy touch. These results suggested that haptic cues from a LT were no reliable sensory trigger for postural responses but that they increased the sensitivity of the response scaling of older adults. Johannsen et al. (2007) aimed to extent the study by Dickstein et al. (2003), which only focused on the initial automatic response (first 75 ms) following a perturbation. They explored the effect of a passive stimulus on the time course of the postural response of healthy young participants during and within 4 s after a perturbation. The results showed that the variability of the COP velocity in response to a passive pull to the participant's arm (held horizontally in front of the body) reduced more quickly due to haptic supplementation by a PS. Thus, balance was restored faster with additional sway-related cutaneous cues than in conditions without haptic cues.

These two above-mentioned studies suggested the potential of haptic cues provided by a fixed support to improve the reactive balance of young and older participants. The response scaling was improved (first 75 ms) and balance was restored more quickly within the 4 s following a perturbation with the help of haptic supplementation.

In the present study, we aimed to apply the mobile-stick experimental paradigm to a situation of sudden support-surface translations that is, to reactive balance. Accordingly, the role of relative movements of the mobile stick gains even more importance than in our previous studies as the stick movements were to be amplified in the mobile-support conditions due to the translational perturbation. To our knowledge, the effect of this kind of relative movement between the lightly-gripped stick and the environment, when the body is moved in space, has not been studied until now. Few studies simply tested the effect of a LT during actual or simulated body movements in space, where the finger slid on the stationary light-touch support ([Kazennikov et al., 2005], slow support-surface translation; [Dickstein and Laufer, 2004, Fung and Perez, 2011], walking on a treadmill). Kazennikov et al. (2005) observed a less stabilizing effect of a LT on a fixed rail when the platform underneath the rocker board moved very slowly back- and forward and, thus, when the finger slid on the rail. The authors concluded that the reliability of the haptic cues determines whether they can be used to build a reference frame for postural control and that haptic cues from a sliding finger are less appropriate to this end. Dickstein and Laufer (2004) showed a stabilizing effect of a LT on a fixed rail on locomotor performance of young adults (which caused a decrease in COM variance; see also [Fung and Perez, 2011], older adults and older chronic stroke patients). As locomotor performance improved even though a slip between the fingertip and the light-touch rail occured, the authors concluded that haptic cues serve as a sensory anchor for the spatial orientation of the body to the environment and earth vertical. The results of these three studies encouraged us to further investigate the effect of a mobile stick that moved with the moving stick-user. Two possible outcomes could be anticipated concerning the effect of relative stick movements on the ground. The ability to maintain stable postural behavior during sudden support-surface translation that is, the system's robustness could change in two different ways due to haptic cues. On the one hand, it could remain unchanged when provided with additional haptic cues as the increased complexity of the stick-arm system would increase the cognitive effort needed for multisensory integration and sensory transformations to a common reference frame [Jeka et al., 2000, Sozzi et al., 2012]. This could be the case especially in older adults with deficient central processing [Horak et al., 1989, Teasdale et al., 1991] and therefore preclude the efficient use of haptic cues. On the other hand, the system's robustness could increase as the amplified movements of the stick would amplify the sway-related haptic cues from the interaction with the environment, thereby facilitating multisensory integration and postural control [Hausbeck et al., 2009, Rogers et al., 2001].

According to Newell (1986)'s model, we manipulated in the present experiment the environmental (sensory cues), the subject-related (age groups) and the task-inherent (sudden support-surface translation) factors of postural control.

7.2. Aims and hypotheses

We hypothesized that relative stick movements on the ground provide useful sway-related orientation cues that can be used to improve postural control and increase the system's robustness to sudden support-surface translations. The goal in this challenging postural task is to regain stable behavior as quickly as possible and so we hypothesized that the time to the first postural correction after the end of the perturbation should be reduced by haptic supplementation. If haptic cues during reactive balance led to increased reliance on ankle and hip stiffness to reduce body sway, as suggested by Johannsen et al. (2007), then the peak sway amplitude due to the perturbation (reflecting the first COP response to the perturbation) should be reduced when provided with additional haptic cues. If the contrary was true, then the postural control system should be able to reduce the reliance on increased stiffness-control due to haptic supplementation, as has been shown in studies II and III of the present work. As a sign for a more flexible use of DoF to cope with disturbance [Nardone et al., 2000] and/ or for additional delays needed to integrate haptic cues, the peak sway amplitude should increase if additional haptic cues are available. Based on findings by Dickstein et al. (2003), we hypothesized that older adults can reduce the time needed for the first postural correction due to additional haptic cues as a sign for more rapid and efficient postural control.

7.3. Materials and methods

7.3.1. Participants

Twelve young (2 women and 10 men, mean age 26.6 ± 2.0 years) and eleven older participants (5 women and 6 men, mean age 74.5 ± 5.7 years) took voluntarily part in the experiment. They were right-handed, physically active and had no self-declared musculoskeletal injuries, or perceptive, cognitive and motor disorders that might affect their ability to maintain balance or to understand task instructions. The experimental protocol was presented to all participants, which gave a written consent before undergoing the experiment. The protocol was approved by a local ethics committee and has therefore been in accordance with the ethical standards laid down in the declaration of Helsinki.

7.3.2. Task and experimental design

Five experimental conditions were tested: a translation condition (TRANS) on a sliding force platform and four conditions of haptic supplementation on the sliding platform (a fixed- and three mobile-support conditions). In all conditions, participants stood directly in the center of the force platform and the force platform alternately moved forward and backward (amplitude 62 mm, speed 0.1 m/s, 8 s break between successive perturbations). Each experimental condition lasted 75 s, in which four forward and four backward trials were presented to the participants. Each trial lasted around 8.6 s. Each condition started with a forward translation and finished with a backward translation (Figure 22). A forward translation of the platform resulted in a backward postural reaction that had to be counteracted by the balancing participants and a backward translation of the platform resulted in a forward postural reaction of participants. Haptic supplementation was provided through the LG of a stick with the right hand (chapter 2.4.1.). The fixed or mobile support was orientated in the plane of greatest instability that is, in the AP direction. The mobility of the stick and its resistance offered to body oscillations were manipulated in four conditions of haptic supplementation: 1) a fixed- (LGf), 2) a blocked-support condition (LGb), 3) a rough- (LGr) and 4) a slippery-surface condition (LGs). Participants did each condition with EO and with EC. Half of the participants started with EO and the other half with EC.

In all conditions, participants were asked to maintain a natural upright standing posture with both arms held straight along the body. The feet of the participants were placed at hip-width, side-by-side and the toeholds were positioned in a distance of 20 cm, in an angle of 30°. They were asked to fixate a point in eye height at 1.5 m on a wall. The stick was always out of sight of participants. In all conditions, they were instructed to not move their arms or feet and to regain stability as quickly as possible. In case of great instability or loss of balance, participants could touch the safety bars, the perturbation was interrupted and the corresponding condition was rejected and repeated.

Breaks lasted 120 s between conditions. Each condition started when participants were able to stand quietly without exceeding the force threshold (< 1.6 N). The total experimental session lasted about 1 hour.

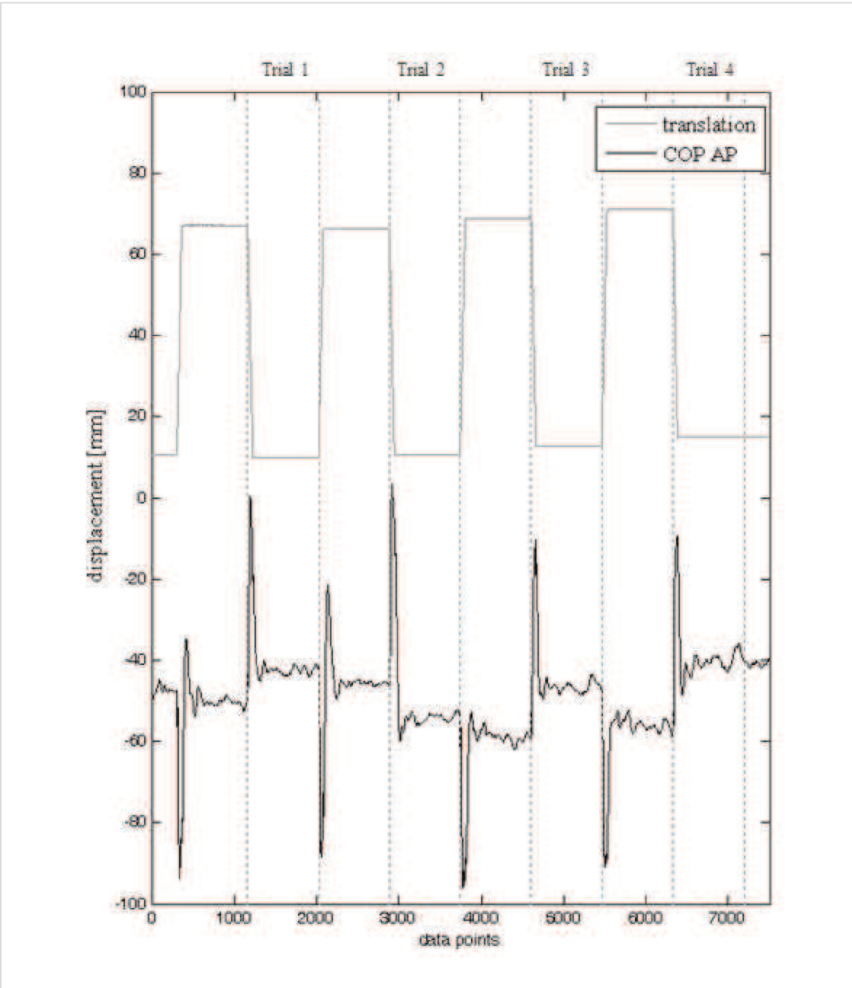

Figure 22: The translation profile and an example for the postural reaction represented by the COP trajectory
The dotted lines indicate the beginning and the end of each backward trial

7.3.3. Apparatus and measures

Data were collected by means of a force platform (SYNAPSYS POSTUROGRAPHY SYSTEM®, SYNAPSYS SA, Marseille, France, Figure 23) that measured the three components of the resultant ground reaction force to determine the COP trajectories. Data were sampled at 100 Hz. Unfiltered data were analyzed offline with the help of Matlab 7.0 (The MathWork®, Inc., Natrick, MA, USA). COP trajectories were computed in the AP direction and two dependent variables, a spatial (peak amplitude of the COP) and a temporal one (time to first correction of the COP), were calculated from these data (see Table 6, for calculation details).

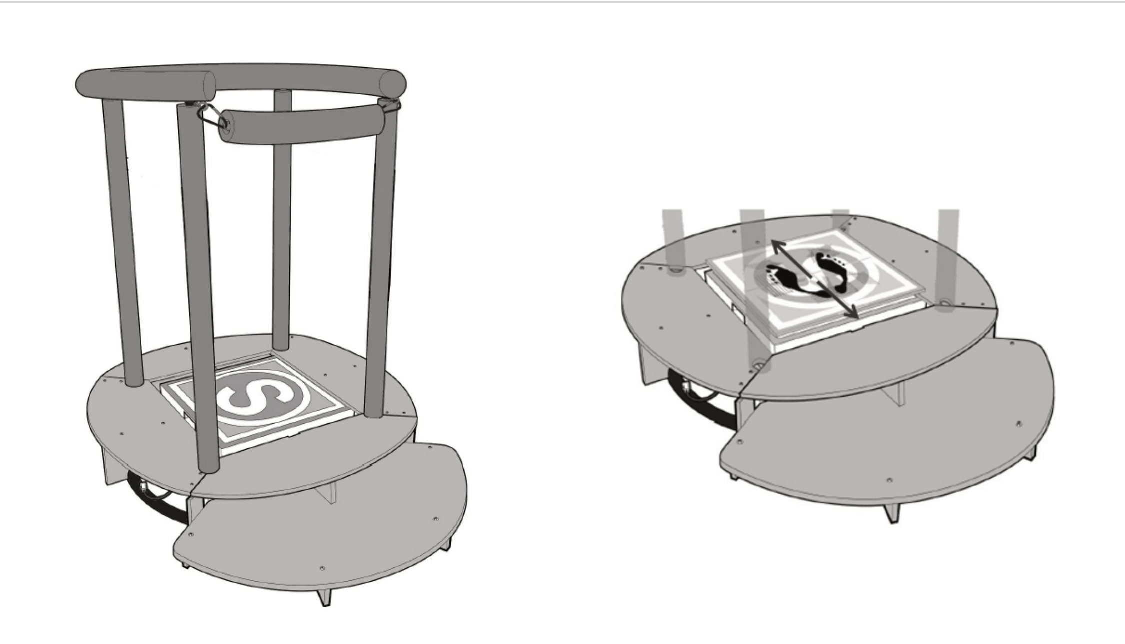

Figure 23: SYNAPSYS POSTUROGRAPHY SYSTEM® with safety bars (on the left) and the two possible directions of the platform translations (on the right)

To deal with the issue of habituation during the 8 perturbations (2 directions x 4 trials) within each condition, we analyzed only the first trial of each condition. Moreover, only the COP reaction to backward perturbations was analyzed (see [Dickstein et al., 2003]). This choice was due to the fact that the study aimed to test the effect of haptic supplementation in the most natural visual environment (optic flow stimuli with radial contraction as, for example, during locomotion) and in a situation that was perceived as unthreatening by the participants (especially older adults might have fear of backward body movements).

Table 6: Variables extracted from the COP trajectories in the conditions TRANS, LGf, LGb, LGr and LGs

Variables	Backward translation
Peak amplitude (PA) [mm]:	Maximal forward displacement after the beginning of the translation
Time to first correction (TC) [s]:	Difference between the index of the local maximum within 10 data points after the end of the translation and the index of the local minimum between this point and 200 data points.

Thus, the COP data of the first backward trial in each condition was used to calculate the PA [mm] and the TC [s] (Figure 6) and to carry out three-way ANOVAs with the between-participant factor group (young vs older) and the within-participant factors eyes (open vs closed) and condition (TRANS, LGf, LGb, LGr and LGs). Normality was checked by means of Kolmogorov-Smirnov tests. Significant effects were further analyzed using Newman-Keuls post-hoc tests (threshold of significance at $P<0.05$).

7.4. Results

In the following, we present the effects of haptic supplementation on the postural reaction to backward translations of young and older participants as reflected by the peak amplitude and the time to first correction of the COP. The differences described in the following were all significant or showed a trend ($P=0.06$), even though the results of the post-hoc tests are not presented in detail.

7.4.1. Peak amplitude

The analysis of the PA revealed an effect of eyes ($F(1,21)=9.05$, $P<0.05$**), condition ($F(4,84)=4.18$, $P<0.05$**) and a tendency for an interaction effect of condition and age ($F(4,84)=2.44$, $P=0.053$, Figure 24). In conditions with EO, PA was significantly larger when compared to conditions with EC. Moreover, PA in the TRANS condition was significantly smaller when compared to three conditions of haptic supplementation (LGf, LGb and LGr). Similarly, the analysis revealed a tendency for a difference between the TRANS and the LGs condition ($P=0.053$). The conditions LGf, LGb, LGr and LGs did not differ significantly from each other. We report that the PA occured at around 350 ms (after the beginning of the translation) in both age groups, even though the time to peak amplitude was not further analyzed in the present study.

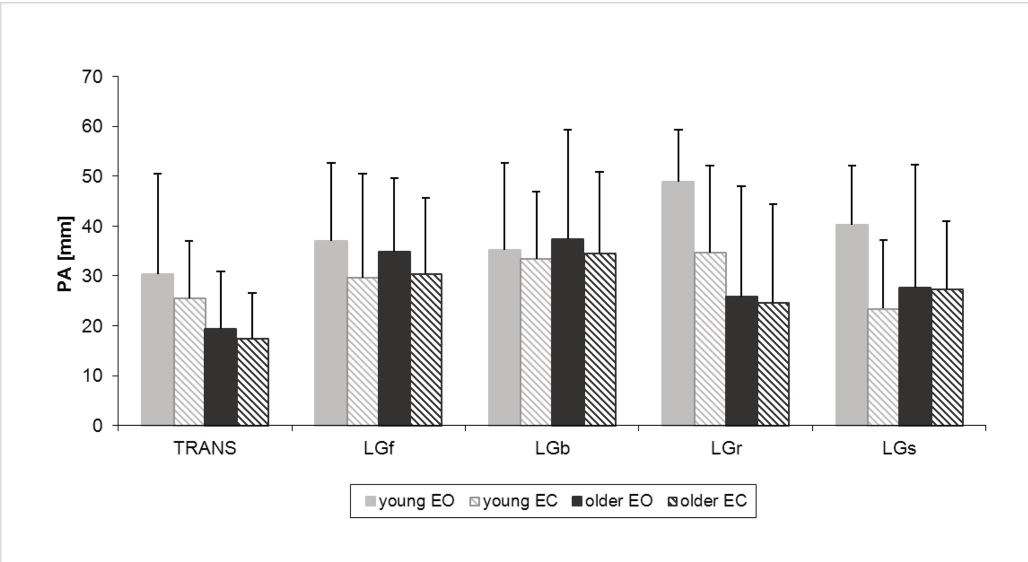

Figure 24: Peak amplitude (PA) for young and older participants with EO and EC in five experimental conditions (mean and standard deviation)

7.4.2. Time to first correction

The analysis of the TC revealed an effect of age ($F(1,21)=9.79$, $P<0.05$**), condition ($F(4,76)=2.50$, $P<0.05$*) and an interaction effect of condition and age ($F(4,76)=3.09$, $P<0.05$*, Figure 25). The post-hoc decomposition of the interaction effect of condition and age revealed significantly higher TC in the TRANS condition when compared to all conditions of haptic supplementation (LGf, LGb, LGr and LGs) in young participants. These latter four conditions (LGf, LGb, LGr and LGs) did not differ significantly from each other. Concerning older participants, no significant difference between experimental conditions (TRANS, LGF, LGb, LGr and LGs) was found.

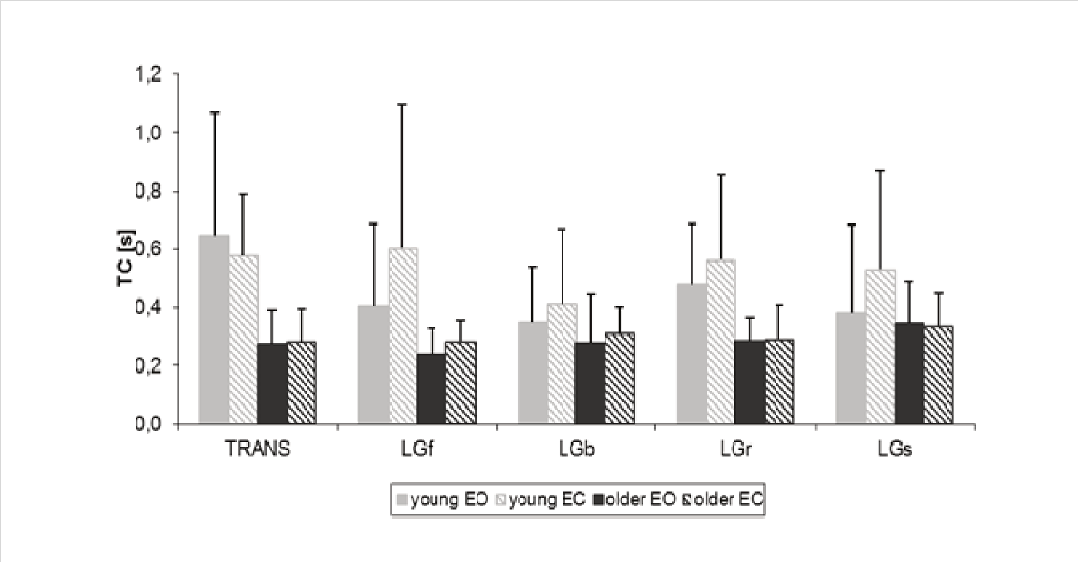

Figure 25: Time to first correction (TC) for young and older participants with EO and EC in five experimental conditions (mean and standard deviation)

7.5. Discussion

The results of the present study confirmed our main hypothesis that haptic supplementation provided by the LG of a mobile stick increases the system's robustness to a sudden backward support-surface translation. However, this effect applied prominently to young adults. In this challenging task, older adults were less affected by haptic supplementation. In the following, we discuss the findings of this study in some detail.

In conditions with EC when compared to those with EO, we observed smaller peak amplitude of the COP in all participants. In the TRANS condition, the peak amplitude was also smaller when compared to conditions of haptic supplementation (LGf, LGb, LGr and LGs (P=0.06)). These results might suggest that participants use a strategy of a rigid body in response to the backward translation when vision is restricted or no additional haptic cues are available. This strategy appeared to result in reduced peak amplitude in response to a perturbation. Thus, a rigid body, in challenging conditions (TRANS) or in absence of vision (EC), might help to maintain balance without approaching individual stability limits. Nardone et al. (2000) observed a rigid behavior of older adults in a similar challenging postural task. The authors showed stronger positive correlations between the lower and the upper body of older adults standing on a rotational platform with EC when compared to younger adults. Consistent with these findings, our results suggested that the observed behavior in young and older participants on the sliding platform is a strategy to reduce available DoFs in order to more safely counteract the perturbation [Nardone et al., 2000]. Due to the lack of kinematic data about the response pattern of the body segments, this hypothesis remains to be confirmed.

Quiet the opposite, haptic supplementation resulted in larger peak amplitude in response to the perturbation. The larger PA when haptic cues are available might indicate that the CNS presumably necessitates a short additional time delay, in which the COP continues to move away from equilibrium, in order to integrate additional haptic cues before the perturbation can be counterbalanced due to feedback-based postural corrections. This response pattern did not appear to be influenced by higher age. Interestingly, a similar reponse pattern of the peak amplitude was observed when vision was available. The CNS appeared to integrate additional orientation cues in the same way, independent of whether they are “non-posture specific” or “posture-specific”. The PA in this study occured at around ~350 ms, which corresponds to the commonly observed delays between contact forces applied during a LT and the following COP reaction during quiet upright stance [Jeka and Lackner, 1994]. Thus, these results might suggest that haptic cues drive postural corrections but that to do so a short additional delay is needed to integrate the haptic cues. Finally, they suggested that all participants benefit from the four different types of haptic cues, independent if provided by a fixed or mobile support.

Corresponding to a later postural response (after the end of the translation, > 600 ms), we observed that only younger participants reduced the time needed to perform the first correction of the COP (TC) due to haptic supplementation (LGf, LGb, LGr and LGs, ~450 ms) when compared to the TRANS condition (~600 ms). Accordingly, these results suggested that young participants shorten their reaction when additional haptic cues are available, independent of the stability of the support. These results are consistent with results by Johannsen et al. (2007) who found an earlier suppression of postural sway in young participants due to a passive stimulus during reactive balance (reflex pull to the horizontally-held arm). Thus, sway-related orientation cues from a passive stimulus as well as those from a LG of a mobile support appeared to improve the system’s robustness to perturbation and enable it to perform earlier postural corrections. As for haptic perception, the CNS combines cutaneous and proprioceptive cues [Krishnamoorthy et al., 2002, Rabin et al., 2008], Sozzi et al. (2012) hypothesized that it is associated to a computationally heavy integration in order to locate the arm, the hand and the finger. Consequently, one could have expected that the increased complexity of the stick-arm system in the mobile-support conditions would further increase the cognitiv effort needed for the integration of haptic cues. Quite the contrary, the benefit of haptic cues in the mobile-support conditions confirmed that the increased complexity of the stick-arm system did not prevent the CNS from integrating haptic cues in order to improve postural control.

In contrast, older adults did not behave in the same way. Indeed, they showed shorter TC than young adults in all conditions (older: ~300 ms and young: ~500 ms) and did not further reduce the TC due to haptic supplementation. These results suggested that older participants did not take advantage of additional haptic cues to perform earlier postural corrections in the present perturbing postural task. Most likely, this was due to the already shortened TC in older adults without haptic supplementation that suggested an age-related strategy to perform the challenging task when no additional cues were provided. Taken together, these results suggested that older adults could integrate haptic cues to modify the initial postural reaction but not to further reduce the time to the first postural correction. It appeared to be the case that older adults chose a strategy (different to that of younger adults) that enabled them to react earlier than young adults once the perturbation stopped. The parameter TC, however, does not indicate if the earlier first postural correction of older adults led to an equally efficient reduction in body sway than of young adults. This faster reaction of older adults was presumably due to increased stiffness of the system by means of muscle co-contractions [Allum et al., 2002]. Most likely, this age-related difference in stiffness-strategy was due to an anticipation of the perturbation by older adults as part of a cautious or fearful behavior in the presence of a potential risk to fall [Maki et al., 1991]. This hypothesis about a stiffness-strategy chosen by older adults should, however, be tested in futur studies by assessing the activation and the level of co-contraction ot the involved postural muscles.

8. General discussion

8.1. Objectives and hypotheses of the present work

The present work aimed at systematically exploring the effect of a LT provided by a mobile support on postural control of young and older adults in different situations, such as standing and sitting. At the very beginning of our work, there was evidence in the literature for the effect of a LT (light touch on a fixed support) or a PS (externally applied passive “scratch” to the skin) on postural stability of older adults during quiet upright stance [Baccini et al., 2007, Reginella et al., 1999, Rogers et al., 2001]. Moreover, some studies suggested that older adults even benefited more from haptic supplementation than their younger counterparts [Baccini et al., 2007, Rogers et al., 2001]. Therefore, and despite findings about alterations of the sensory systems [Goble et al., 2009, Sturnieks et al., 2008] or central integration [Zec, 1995] with higher age, we hypothesized that older adults can make use of haptic cues from a mobile support to improve self-motion perception and thereby postural control. In particular, we hypothesized that increased resistance offered by the (mobile) support increases the stabilizing effect of haptic cues since it amplifies the sensory information associated to body sway.

In spite of the evidence supporting the benefit of a LT on various supports (fixed and mobile) and in various postural tasks (quiet stance, rocker-board stance and treadmill-walking), uncertainty still remained about whether a mobile support that moves with the swaying body can provide orientation cues that are functional for postural control. Similarly, the underlying mechanisms of these (potential) effects remained to be explored. The remaining uncertainty was presumably due to the different experimental setups and the various types of light-touch supports that have been used (fixed support, filaments, loads and canes). Finally, this inconsistency in experimental strategies precluded a systematic exploration of the effect of a mobile light-touch support and the comparison of the different existing results.

Several authors suggested that the availability of a fixed reference point in the environment provided by a LT on a fixed support is of crucial importance to provoke a stabilizing effect on postural stability [Holden et al., 1994, Jeka and Lackner, 1994]. Others, however, put forward that a fixed reference point is dispensable if sway-related changes in cutaneous and proprioceptive cues are available provided by a LT on a mobile support [Krishnamoorthy et al., 2002, Lackner et al., 2001]. Results observed in studies using the passive-stimulus paradigm also underlined the importance of sway-related cutaneous information for postural stabilization [Menz et al., 2006, Rogers et al., 2001].

In order to compare the effect of a LT on either fixed or mobile supports, a prerequisite of the present work consisted in the design and use of a mobile-stick experimental paradigm. We combined the light-touch paradigm (light contact with the environment via a mobile support) and the passive-stimulus paradigm (sway-related scratch stimuli of the mobile support). Owing to this new paradigm, we explored whether and how the CNS of healthy young and older adults can make use of haptic cues provided by the LG of a mobile support in order to improve postural control. Accordingly, we expected to contribute to the better understanding of multisensory integration processes. Inspired by the effect of the PS, we hypothesized that sway-related information can be mediated by a mobile support that is free to move with the oscillating body and that allows the quasi-static or moving user to "interact" with the environment. Thus, if the LG of a mobile support was shown to be effective in reducing body sway this would corroborate the interpretation in favor of sway-related orientation cues that facilitate postural control and challenge the one in favor of a fixed reference point. In addition, we hypothesized that the stabilizing effect of haptic supplementation is independent of the stability of the light-grip support. More precisely, even in absence of a fixed reference point, a LG of a mobile support was expected to improve postural control if the support provided sufficient resistance to body sway and thereby created sufficient sway-related haptic feedback.

Our motivation to undertake the present work was also based on the fact that both researchers and clinicians have evoked the potential benefit of haptic cues provided by the LT of a cane in everyday life of older adults or patients [Bateni and Maki, 2005, Jeka et al., 1996]. Nevertheless, portable assistive devices (such as a cane) that could provide sway-related cues via their interaction with the environment remain rare. Classically, in the clinical routine, the reinforcement of postural control mechanisms consists (among others such as physiotherapy) in the prescription of walking aids to preserve postural stability ([Bateni and Maki, 2005], for review). These walking aids are currently prescribed as a mechanical support to severely impaired older adults or fallers. However, one could speculate that most people suffering from infra-clinical alterations of postural control might benefit from “light” haptic assistance in order to improve postural stability and locomotor performance in everyday life.

Taken these theoretical and clinical aspects together, it appeared to be a crucial step to explore the effects of sway-related haptic supplementation provided by a mobile support in order to understand whether additional haptic cues (provided by a cane-like support) could be useful for older adults, and whether these cues could potentially be provided by a portable haptic assistive device.

We were also interested in the potential effect of haptic supplementation on postural control of sitting. The effect of a LT or a PS during sitting has not been explored in the literature. In general, even though standing [Kiemel et al., 2008] and sitting postural control [Reeves et al., 2007] are currently modelled in the same way, only few works have tried to compare postural control mechanisms in both tasks (see [Preuss and Fung, 2008, Vette et al., 2010], for exceptions). Moreover, a lot of work in the domain of sitting postural control focused on deficient postural control of patients with low back pain [Radebold et al., 2001, Van Daele et al., 2009] or stroke [Genthon et al., 2007, Perlmutter et al., 2010] but scarcely studied the postural control system during normal aging. The main common principle of standing and sitting postural control models is that the CNS uses feedback mechanisms to maintain posture in both biomechanically different tasks [Kiemel et al., 2008, Reeves et al., 2007]. Consequently, another objective of the present work was to explore the effect of haptic supplementation on postural control of sitting in healthy young and older adults. In addition, we aimed to investigate if haptic cues from a mobile support can compensate for missing visual cues. Based on the assumption of similar feedback control principles during sitting and upright standing, we hypothesized that additional haptic cues can improve postural control of sitting and that the CNS can use haptic cues to compensate for missing visual cues.

Finally, the present work represented a preliminary step to better understand whether and how the CNS can use haptic cues from a cane-like support to control posture in different, more dynamic postural tasks (i.e., standing on a rocker board or during sudden support-surface translations). Besides its theoretical interest, this work was also conducted to clear the way for future research about the effect of haptic assistive devices during locomotion. In this perspective, we hypothesized that, even when perturbed, the postural control system can integrate haptic cues from a mobile support and use them to improve the recovery from perturbation. As time delays are very important when regaining stability during support-surface translations and as the integration of haptic cues might necessitate additional cognitive effort [Sozzi et al., 2012] and therefore additional time, it was worth assessing this issue. We hypothesized that participants can reduce the time to the first postural reaction due to haptic cues.

To achieve these objectives and to test the above-mentioned hypotheses, the mobile-stick experimental paradigm was used in different postural tasks. In contrast to classical light-touch studies, in which fixed or “mobile” (nonetheless never cane-like) supports were used, a lightly-gripped stick or a pen was utilized in the present studies to provide haptic supplementation. The manipulation of the mobility and resistance of these supports (mainly in the direction of greatest postural instability) permitted us to vary the types of sensory cues (related to a fixed spatial referent or sway-related cues) available to the CNS of participants.

8.2. The effect of haptic supplemention on postural control

The results observed in all five experiments globally confirmed our general hypothesis about the effect of haptic supplementation on postural stability of healthy young and older adults. We will concentrate on five aspects to discuss the effect of haptic supplementation in detail: 1) the stability of the light-grip support, 2) the benefit of older adults from haptic supplementation, 3) the resistance offered by the support against body sway, 4) the benefit of haptic supplementation during sitting and 5) the benefit of haptic supplementation during perturbed standing on coordinative patterns of the leg and trunk segments.

8.2.1. The stability of the light-grip support

The results of the different studies in the present work (older participants in study V represented an exception) confirmed that all participants increase both postural stability and the system’s robustness to perturbation when a LG was provided. This effect was independent of the mobility of the light-grip support. As expected, even in absence of a fixed reference point, the light contact with a mobile support improved postural stability during quiet stance (studies I and II), during unstable sitting (study III), during rocker-board stance (study IV) and to a certain extent improved the system's robustness to sudden support-surface translations. These results challenged the classical interpretation about the necessity of a fixed reference point in the environment to build a reference frame for postural stabilization [Holden et al., 1994, Jeka and Lackner, 1994]. In contrast, our results suggested that the sway-related cues provided by the light contact with the environment (even if mediated by a mobile support) can be successfully integrated by the CNS together with other sensory cues and can be used for postural control [Krishnamoorthy et al., 2002, Lackner et al., 2001]. Thus, under certain conditions, haptic cues from cutaneous mechanoreceptors and muscle spindles of the fingers and arm that are not commonly relevant for the control of upright posture ("non-posture-specific") come to play a functional role in postural control. Interestingly, results of the study on sitting postural control (study III) suggested that, in order to preserve stable behavior when another commonly used "posture-specific" sensory source is withdrawn (vision), the function of haptic cues actually becomes comparable to that of the lacking sensory source (see also [Hausbeck et al., 2009, Jeka and Lackner, 1994]). The effect of haptic cues from a mobile support presumably reflects the efficiency of sensory reweighting processes that enable the CNS to flexibly combine different sensory cues, including those that are not commonly used for postural control. The effect of haptic cues in young healthy participants during quiet stance with available vision (study I) strongly suggested that additional haptic cues enrich the sensory environment, improve self-motion perception and thereby postural control. In contrast to this "supplementation-effect" interpretation, the benefit of haptic cues in older adults (study II) or in conditions of visual restriction (study III) rather led us to a "substitution-effect" interpretation. This means that additional haptic cues can help the CNS to disregard inaccurate or missing sensory information and to use haptic cues instead [Hausbeck et al., 2009, Jeka et al., 2000, Peterka, 2002, Oie et al., 2001]. These two interpretations, even if presented separately, are not exclusive and it seemed reasonable to state that the CNS can integrate "posture-specific" and "non-posture-specific" sensory cues to take advantage of sensory redundancy or complementarity depending on the postural task and the sensory environment.

Following the line of argumentation by Lackner et al. (2001), our results would suggest that haptic cues provided by the mobile support improved postural control due to the interaction of the stick or pen with the stable environment. This means that the support plays the role of a "mobile mediator" but that the effective light-touch support that represents a spatial referent is the stable surface underneath the support. Lackner et al. (2001) defended the point of view that useful haptic cues can be provided by the LT of a mobile support if this support did not move beyond certain spatial limits. In this way, the authors extended the notion of a 'fixed reference point' (LT on a fixed support) to a 'fixed reference region' (LT mediated by a mobile support that does not move beyond a certain stable region). Several findings in the domain of sensory supplementation, however, challenged this interpretation. For instance, findings about the stabilizing effect of hand-held loads are to be mentioned [Kazennikov et al., 2008, Krishnamoorthy et al., 2002]. Sway-related inertial forces in the hand due to the hand-held load appeared to improve self-motion perception and postural stability without contact with the stationary environment. Similarly, sensory-substitution devices (e.g., BrainPort Balance Device) have been shown to provide useful sensory cues and stabilize the user without a contact of the user with the stationary environment. Biofeedback about the head orientation from these devices substitutes the system via another sensory modality (i.e., vibration as a modality of cutaneous receptors on the tongue) and has been found to stabilize, for example, older adults with chronic balance dysfunction during upright stance [Danilov et al., 2007]. In summary, these findings demonstrated that the CNS can be supplemented or that missing sensory cues can be substituted in multiple ways. Not the contact with the stationary environment but the sway-related character of additional sensory cues appeared to be the decisive factor for postural stabilization through haptic supplementation. We hypothesized that the light grip of a cane-like mobile support in our study owed its stabilizing effect, first, to the sway-related haptic cues created at the level of the fingers (and arm) and, second, to the resistance provided by the support (but not to the availability of a fixed reference region underneath the support).

8.2.2. The benefit of older adults from haptic supplementation

In three of our studies (studies II, III and V) we compared the effect of haptic cues on postural stability or the system's robustness to perturbation of young and older healthy participants. Results confirmed (studies II and III) that young and older participants benefited to the same extent from haptic supplementation. It is noticeable that this was the case even though clinical tests of cutaneous sensitivity showed an age-related decline of spatial acuity at the fingertip (study III). These changes in spatial acuity that presumably result from changes in innervation density of slow- and fast-adapting mechanoreceptors of the fingertip [Tremblay et al., 2005] were, however, not pathological. According to these results, the age-related decline in spatial acuity at the fingertip does not suspend older adults from benefits of haptic supplementation [Tremblay et al., 2004]. Consequently, these benefits presumably originate at a central rather than a peripheral level of the nervous system (see also [Dickstein et al., 2001], neuropathy patients). During postural control of standing (study II) and sitting (study III), our results suggested that haptic supplementation has an effect on open-loop and closed-loop postural control mechanisms of young and older adults. More precisely, in the framework of Collins and De Luca (1993), these results suggested that haptic supplementation reduces (over short time intervals) the reliance on increased muscle activity of involved muscles (steady-state muscle activity) and leads (after longer time delays) to well-coordinated postural corrections. In older adults, the higher age-related open-loop stochastic activity of the COP could even be compensated due to haptic supplementation [Albertsen et al., 2012]. Without additional sensory cues during unstable sitting, stiffening the trunk appeared to be part of the strategy of the older adults to master the challenging sitting task ([Collins et al., 1995], for consistent interpretation). In conclusion, haptic cues appeared to decrease leg stiffness during standing (study II) and trunk stiffness during sitting (study III) and improve feedback control mechanisms of young and older adults.

However, the effects of haptic supplementation on postural control of older adults during sudden support-surface translations (study V) constituted an exception. Older adults did not take advantage of haptic cues in the same way than their younger counterparts in this challenging task. More precisely, they did (just as younger participants) increase the peak amplitude of the COP after perturbation due to haptic supplementation. On the contrary, they did not reduce (as did younger participants) the time to the first correction of the COP after the end of the perturbation. More precisely, all participants showed larger peak amplitude of the COP due to haptic supplementation when compared to conditions without additional cues. As all participants successfully achieved the challenging postural task, the larger peak amplitude might not exemplify higher instability. These results rather suggested that the CNS effectively integrates haptic cues. However, to do so it needs slightly more time, in which the COP continues to move away from equilibrium, before the perturbation can be counterbalanced via feedback-based postural corrections. On the contrary, the reduced peak amplitude in the TRANS condition (without additional cues) presumably is due to higher amounts of muscle activity or co-contraction to stiffen the system and to resist the perturbation. In conclusion, a strategy of reduced stiffness and therefore a more flexible system seemed to be more appropriate (less energy-consuming) in situations where precise motor control is required [Reeves et al., 2007].

As a later postural response (after the end of the translation), we observed that only younger participants reduced the time needed to make the first correction of the COP when supplemented. Older adults did not behave in the same way. They initially showed shorter time to the first correction of the COP than young participants (older: ~300 ms and young: ~500 ms) and did not further reduce this time due to haptic supplementation. This might suggest a strategy chosen by older adults consisting in increasing stiffness to maintain stable behavior after the end of perturbation which was not influenced by the presence or absence of additional haptic cues. Young participants, however, appeared to make use of haptic cues to shorten their response delay. Most likely, this age-related difference in stiffness-strategy was due to the anticipation of the perturbation by older adults as part of a cautious or fearful behavior [Maki et al., 1991].

8.2.3. The resistance offered by the light-grip support against body sway

By using the mobile-stick experimental paradigm that combined the two main features of the LT and the PS the results confirmed that higher resistivity of the surface underneath the mobile support increases its stabilizing effect. In this perspective, the effects of haptic supplementation in the rough- and the slippery-surface conditions were of special interest. In the literature, the study by Jeka and Lackner (1995) is the only to compare the effect of a LT on a slippery or a rough surface. In both conditions, postural stability improved. Moreover, Rogers et al. (2001) showed a more pronounced stabilizing effect of a PS when the “scratch” stimulus was provided at higher parts of the body. From these observations, we expected to amplify sway-related haptic cues through the interaction of the mobile support with a rough surface (when compared to a slippery one). Consequently, the stabilizing effect should increase in this condition of increased resistance against body sway. The actual difference between the effect of haptic cues in the rough- and the slippery-surface conditions confirmed, at least in part, the above-mentioned hypothesis. The effect of haptic cues in the rough-surface condition was similar to the one in the fixed-support condition, which suggested that the provision of a fixed spatial referent is dispensable to improve postural stability if sway-related cues are provided. In contrast, the less consistent effect of haptic cues from the interaction of the mobile support with a slippery surface deserves to be discussed. Young participants during quiet stance (study I) did not benefit from haptic supplementation in the slippery-surface condition. Only older adults during upright stance (study II) reduced the mean total power of the COP frequency spectrum in all different conditions of haptic supplementation, including the slippery-surface condition. During unstable sitting (study III), young and older participants benefited from all four types of haptic cues, including the slippery-surface condition. During rocker-board stance (study IV), the slippery-surface condition showed a less consistent stabilizing effect when compared to all other conditions of haptic supplementation. Only the variability of the COP was reduced in this condition (not the angular displacements of the two body segments). And finally, as reported above, during sudden support-surface translations, only young participants could make use of all types of haptic supplementation, including the slippery-surface condition. Taken together, the results of studies I to IV suggested that, when provided in complex postural tasks or when provided to older adults presumably with infra-clinical alterations of the postural control system, even very slight changes in cutaneous and proprioceptive information can improve postural control [Hausbeck et al., 2009, Kazennikov et al., 2008]. Nevertheless, the results suggested that higher resistance offered by the mobile support against body sway amplifies haptic cues available to the CNS and therefore guarantees their stabilizing effect ([Lackner et al., 2001], rigid filaments more effective than flexible ones; [Krishnamoorthy et al., 2002], stable support more effective than mobile one; [Hausbeck et al., 2009], stable quad cane more effective than mobile cane).

8.2.4. The effect of haptic supplementation on sitting postural control

The results confirmed our hypothesis that haptic cues improve postural control of sitting even though the biomechanical system (spine) involved in the task is highly complex and predominantly controlled on the basis of spinal proprioception [Reeves et al., 2007]. When put into perspective with corresponding observations on the control of upright standing, these results strengthened the existence of commonalities of the mechanisms involved in postural control of standing and sitting. These commonalities seemed to exist in spite of the different biomechanical systems that come into play in the two postural tasks. Thus, we can conclude that the effective integration of sway-related haptic cues enhances self-motion perception in both tasks. An important remaining question is whether proprioceptive loss of low-back pain patients [Radebold et al., 2001] and associated postural deficits [Radebold et al., 2001, Van Daele et al., 2009] could potentially be compensated by haptic supplementation. As haptic supplementation appeared to reduce intervertebral and trunk muscle activation during this postural task, we hypothesized that it could potentially also reduce adverse consequences of prolonged sitting postures such as persistent low-level muscular activity and muscle fatigue of sitting workers.

8.2.5. The effect of haptic supplementation on coordinative patterns between the leg and trunk segments

The results of the study about rocker-board stance (study IV) confirmed our hypothesis that haptic supplementation, independent of the mobility of the support, reduces the displacements of the leg and trunk segments. The destabilization by the rocker board appeared to further increase the strong positive correlation between the two body segments that was apparent during quiet stance. These results were consistent with those by Almeida et al. (2006) and suggested that participants choose an ankle strategy to maintain stable behavior on the rocker board (with an even stronger in-phase coupling of body segments than during quiet stance). Haptic supplementation did not change the coordinative pattern during rocker-board stance even though angular displacements of the body segments decreased when provided with additional haptic cues.

In order to study if haptic cues can “reverse” a perturbation-induced hip strategy to an ankle strategy (as a sign of a less challenged system), we would have had to increase the difficulty of the rocker-board task. To justify, however, our choice of rocker board, one has to point at the fact that it was a challenge to combine a high difficulty of the postural task with the basic principle of a LT that is, to not strongly grip the support. This kind of strong grip could have been provoked due to a more challenging rocker-board task. In this regard, the chosen rocker board (study IV) was a reasonable compromise. Owing to the digitizer-pen in the sitting study (study III), we were able to increase the difficulty of the rocker board as the manipulation of the pen might have been easier for participants (when compared to the manipulation of the instrumented stick). The pen could be gripped in an individual way and forces were measured at its front extremity by the digitizer, whereas the grip of the instrumented stick had to correspond to the three badges mounted to the stick handle that controlled the light grip. A further study with a new haptic assistive device (cane) that measures applied forces at the front extremity could enable us to more liberally choose the difficulty of the postural task. We are currently implementing such kind of device.

9. Conclusion and perspectives

We considered the present work as a prerequisite to the study of the effect of haptic supplementation in more complex tasks. In view of the prevention of falls, extending experiments about the effect of haptic supplementation to locomotion will certainly help to determine whether the LT phenomenon is transferable to everyday life. Based on the encouraging results presented in this work, one can speculate that portable haptic supplementation could enhance mobility and autonomy of older adults by enriching the sensory environment, improving self-motion perception and enhancing postural control of the upright standing or moving body. Accordingly, the question still remains of whether sway-related cutaneous and proprioceptive cues from the interaction with the environment mediated by a cane may also facilitate the control of multiple DoFs and, especially, the control of the COM during locomotion.

The perspectives of the present work will be structured along the remaining questions concerning the transfer of the theoretical knowledge about haptic supplementation to the implementation of a portable haptic assistive device that could be potentially useful during locomotion. We will present some possible directions to follow concerning the implementation of a portable haptic assistive device and the use of such a device by older adults during locomotion. In addition, we will briefly present a study in process, in which we applied the mobile-stick experimental paradigm to vestibular patients suffering from postural deficits and reduced mobility.

1) Haptic assistive device and locomotion

As confirmed by the results of the present work, the resistance offered by a mobile haptic support is of crucial importance to guarantee a consistent effect of the provided haptic cues. During locomotion, the resistance by a cane might not be provided by a rough surface that would have to be available at any time underneath the cane extremity. On the contrary, we speculate that a cane should ideally lightly resist to the forward moving user/ or to the COM displacements in order to create haptic cues at the hand throughout the gait cycle. Before developping this idea we will introduce some information about the gait cycle and meaningful parameters extracted during a gait analysis.

The gait cycle is defined by the interval between two successive heel contacts of the same foot. It comprises a single-support phase, during which one foot is in contact with the ground and the contralateral leg swings above the ground (about 40% of the total duration of the gait cycle) and a double-support phase, during which both feet touch the ground (about 60%). During this latter phase, the body is slowed down and balanced before the COM is again propelled. Thus, the COM is constantly accelerated and decelerated during locomotion. Changes in certain parameters of the gait cycle and, thus, in the dynamic control of the COM are indicative of impairments (or adaptations) within the postural control system and instability or falls can result. A gait analysis is a systematic method to extract meaningful spatio-temporal parameters about the gait pattern. Corresponding parameters are (among others) 1) the walking speed and stride frequency, 2) the step length and its variability, 3) the step width, 4) the duration of the double-support phase and 5) the symmetry of steps. It is known that older adults walk slower than their younger counterparts, that they widen their steps and that they spend more time in the double-support phase, as part of a more cautious gait (see [Lord et al., 2007]). Also higher trunk variability has been found in older walkers. In order to “reverse” this cautious gait pattern of older (unstable) adults to a more confident one, it might be beneficial to improve self-motion perception due to additional haptic cues and thereby the dynamic control of the COM acceleration and deceleration. Inspired by our findings about the crucial role of the resistance offered by the support against body sway, we speculate that this knowledge could be used in the design of a portable haptic assistive device. Even if technical details are still unclear, it might be possible to conceive a (vertical) cane that “lightly” resists to the COM displacements. As the handle of the cane is close to the COM (when held vertically), this might be the appropriate location where to provide meaningful haptic cues [Kazennikov et al., 2008]. This kind of resistance (e.g., based on a specific mass distribution inside the device) and the light contact of the device with the ground could facilitate the detection of the COM position and improve locomotor performance.

The design of a portable assistive device providing sway-related haptic cues as well as the exploration of its use by older adults in everyday life are future challenges of our research group and, more generally, of gerontechnologies. For instance, it is still unclear whether older adults or patients would use the portable haptic device (cane) by alternating between a swing and ground contact phase considering only sequential haptic cues during specific moments of the gait cycle (see [Boonsinsukh et al., 2009], stroke patients). Another question is whether the three dimensional movements of a portable device and its pendular movements during locomotion provoked by rhythmic arm and body movements would alter haptic cues over the gait cycle precluding beneficial effects. Encouraging results of the present work were that the highest tested complexity of the stick-arm system during sudden support-surface translations (without strapping the arms to the body) did not prevent the CNS (of young participants) from using haptic cues in order to improve the postural response to perturbation.

Finally, one should determine the optimal level of force cues that has to be generated in the hand to improve haptic perception during locomotion. In this regard, studies using the light-touch paradigm during quiet upright stance in young adults suggested that the function of cutaneous mechanoreceptors of the hand might be optimized if about 0.4 N was applied during the LT to a fixed support [Jeka and Lackner, 1994]. Supplementary data from the study III of the present work (that has not been presented here) confirmed about 0.4 N applied by the mobile pen on the digitizer. Even though forces up to 1 N were allowed in both studies, participants appeared to keep contact at this specific level to improve the function of cutaneous mechanoreceptors and thereby haptic perception. It has also been shown that older participants applied slightly more fingertip force (~0.2 N) during a LT than their younger counterparts to provoke a comparable postural benefit [Tremblay et al., 2004]. Tremblay et al. (2004) concluded that this might be a sign for a compensatory strategy of older adults to overcome their loss in tactile sensation. Future studies are necessary to find a technical solution to efficiently provide haptic information to healthy and sensory-impaired individuals. Even though our findings on older adults with reduced spatial acuity at the fingertip (study III; see also [Dickstein et al., 2001], neuropathy patients) suggested that the benefit from haptic cues originates at a central rather than a peripheral level of the nervous system, we speculate that a haptic assistive device could use the technique of stochastic resonance to enhance haptic perception. This technique has been found to enhance the effectiveness of a LT on a stable support in young participants during quiet upright stance [Magalhães and Kohn, 2011]. The principle objective of stochastic resonance is to activate not only supra-threshold mechanoreceptors but also sub-threshold ones via vibration and to augment the sensory cues available to the CNS. Equipping, for example, the handle of a portable haptic assistive device with this technique could potentially increase the proprioceptive sensitivity of older adults or patients. Also very low-intensity stimuli (such as the ones provided in the present study by the interaction with a slippery surface) could potentially be amplified by stochastic resonance [Magalhães and Kohn, 2011, Priplata et al., 2003]. In conclusion, stochastic resonance could be a possible way to optimize haptic perception of orientation cues provided by a portable haptic assistive device.

2) Clinical applications

From a clinical point of view, a better understanding of the plasticity of sensory integration processes may improve the care and comfort of older adults or patients that are at risk of falling due to peripheral or central (sub-clinical or severe) impairments. In collaboration with clinicians at a hospital in Marseille, we currently study the effect of haptic cues from a mobile stick on vestibular patients during quiet upright stance. In this study, the same mobile-stick experimental paradigm is used as in studies I and II. This work, which is still in process, will help to further understand the influence of haptic supplementation on multisensory integration mechanisms of impaired postural control systems. For example, vestibular patients after neurotomy (one of the groups of vestibular patients tested in the mentioned study) are known to compensate for the missing vestibular input (after surgery) frequently in favor of proprioceptive cues. This compensation exemplifies the neuro-plasticity of the CNS of patients. Thus, we speculate that haptic cues should be effectively integrated by these patients to substitute for the missing sensory cues and improve postural stability and mobility in everyday life.

Hypothetically, research on these remaining questions could lead to the design of a portable haptic assistive device of a new type (informational, biomechanical or both), more adapted to needs and deficits of people that do not (or not exclusively) need a firm biomechanical support. Indeed, haptic supplementation appears to have a potential to be easily incorporated in a low-cost assistive device, which immediately could enhance postural stability. This kind of haptic assistive device would, most likely, have advantages over electrotactile biofeedback devices that are, for example, used in the rehabilitation of vestibular or unstable patients and that necessitate a learning period before their use in order to decode the provided electrotactile cues (e.g., vibration on the tongue). The advantage of haptic cues could be that no learning period has to be undertaken, as the effect of haptic cues occurs naturally and immediately. Thus, the cognitive effort needed to use haptic cues when compared to the use of electrotactile devices might be reduced (precluding thereby a potential reduction in walking speed when used during locomotion or fatigue). We speculate that, beside its potential biomechanical benefit, a portable haptic assistive device could incorporate spatial orientation cues through a LG of the device that is in contact with the environment. Both, the mechanical and the informational function, could at last enhance postural stability in older adults in a variety of everyday-life tasks. Thus, a continuation of the present work will consist in applying this mobile-stick experimental paradigm to locomotor tasks while targeting different groups of participants. It would be beneficial to approach everyday-life situations, in which a haptic assistive device could potentially be of assistance. Of course, attentional, neuromuscular, metabolic, physiological (fatigue) and psychological consequences of such a device should be determined before being proposed to a large audience.

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