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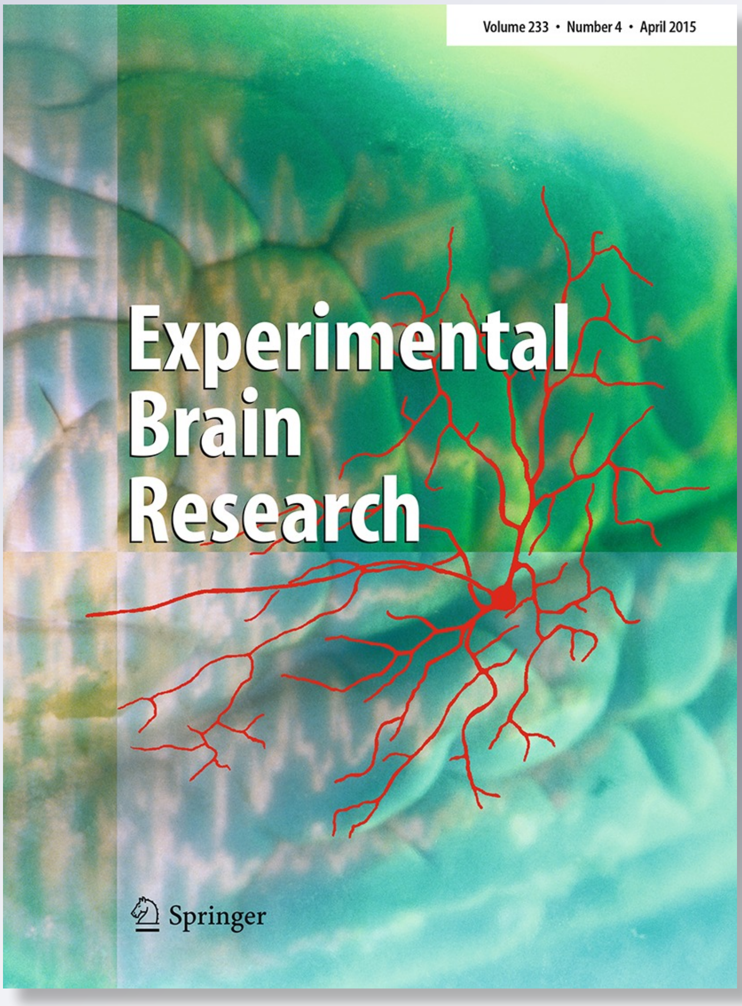

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RESEARCH ARTICLE

Effects of support surface stability on feedback control of trunk posture

Georgia Andreopoulou · Erwin Maaswinkel · L. Eduardo Cofré Lizama · Jaap H. van Dieën

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Abstract This study aimed to examine the interactions of visual, vestibular, proprioceptive, and tactile sensory manipulations and sitting on either a stable or an unstable surface on mediolateral (ML) trunk sway. Fifteen individuals were measured. In each trial, subjects sat as quiet as possible, on a stable or unstable surface, with or without each of four sensory manipulations: visual (eyes open/closed), vestibular (left and right galvanic vestibular stimulation alternating at 0.25 Hz), proprioceptive (left and right paraspinal muscle vibration alternating at 0.25 Hz), and tactile (minimal finger contact with object moving in the frontal plane at 0.25 Hz). The root mean square (RMS) and the power at 0.25 Hz (P25) of the ML trunk acceleration were the dependent variables. The latter was analyzed only for the rhythmic sensory manipulations and the reference condition. RMS was always significantly larger on the unstable than the stable surface. Closing the eyes caused a significant increase in RMS, more so on the unstable surface. Vestibular stimulation significantly increased RMS and P25 and more so on the unstable surface. Main effects of the proprioceptive manipulation were significant, but the interactions with surface condition were not. Finally, also tactile manipulation increased RMS and P25, but did not interact with surface condition. Sensory information in feedback control of trunk posture appears to be reweighted depending on stability of the environment. The absolute effects of visual and vestibular manipulations increase on an unstable surface, suggesting a relative decrease in the weights of proprioceptive and tactile information.

Keywords Postural control · Sensory reweighting · Sitting posture · Sway

Introduction

The human ligamentous spine, devoid of muscular control, is incapable of carrying the weight of the upper body, as the smallest perturbation will cause it to buckle (Crisco and Panjabi 1992). Therefore, in addition to passive structures such as the intervertebral discs and the ligaments, back and abdominal muscles contribute to stabilization of the trunk against perturbations (Panjabi 1992) through modulation of co-activation and the resultant muscle stiffness and damping (Cholewicki et al. 1997; van Dieen et al. 2003) and under feedback control based on the sensory information provided by visual, vestibular, proprioceptive, and tactile afferents (Goodworth and Peterka 2009; Maaswinkel et al. 2014).

The postural control system appears to use multiple sources of sensory information on trunk movement for feedback control. The vestibular and visual systems provide indirect information on motion and spatial orientation of the trunk (Mergner and Rosemeier 1998). The somatosensory system likewise provides indirect information through sensing of shear or pressure induced by motion between body and support area (Lestienne and Gurfinkel 1988; Massion 1992). Also, in studies of whole body control (Lackner et al. 2000) and of trunk control (Maaswinkel et al. 2014) it was shown that tactile information contributes. Proprioceptive information appears to be a more direct source of information on trunk movement and probably the only

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source of information on spinal curvature. Muscle spindles are thought to be the main source of this information (Brumagne et al. 2008), although joint receptors may also be involved (Solomonow 2004).

It has been suggested that the central nervous system (CNS) weighs information from different sensory sources, relative to one another, to generate appropriate feedback commands (Peterka 2002; van der Kooij et al. 2005). Information from multiple systems appears combined also in control of the trunk (Brumagne et al. 2004; Carver et al. 2006; Goodworth and Peterka 2009). An advantage of this reweighting may be that the CNS can adjust gains of sensory inputs from other locations, when the quality of the input from one location decreases due to for example aging or injury (Brumagne et al. 2004).

Sensory weighting in feedback control also appears to be affected by environmental conditions. Studies have shown that effects of triceps surae muscle vibration were less when standing on an unstable than on a stable surface, indicating that proprioceptive information from triceps surae muscles was used less in postural control on an unstable support than on a stable support (Ivanenko et al. 1999; Kiers et al. 2012). This effect has been explained by an altered relation between muscle strain and the body's orientation in the gravitational field on the unstable support (Ivanenko et al. 1999; Kiers et al. 2012). When standing on a rigid surface, foot orientation is fixed; hence, shank angle determines the length of the lower leg muscles and bears a direct relation with the orientation of the body with respect to gravity. This is not the case when standing on a tiltable or compliant surface. Somewhat simplified: the state of the two degrees of freedom (shank angle and foot/surface angle) present on an unstable surface can not be sensed by one degree of freedom (ankle angle) proprioceptive information. In addition, standing on an unstable support would reduce the input into the somatosensory system arising from the contact with the support surface (Pasma et al. 2012). Finally, on an unstable surface movement amplitudes will increase, which, for control of standing postures, has been indicated to cause upweighting of vestibular information (Maurer et al. 2006; van der Kooij and Peterka 2011) and visual information (Fransson et al. 2007; Polastri et al. 2012; Asslander and Peterka 2014) relative to proprioceptive information.

The goal of the present study was to examine the effects of surface conditions on the importance of different sources of sensory information, as reflected in the effects of sensory manipulations on mediolateral (ML) postural trunk control. We hypothesized interaction effects between surface conditions and the sensory manipulations, reflecting larger effects of visual and vestibular information on an unstable surface than on a stable surface and a reduced effect of proprioceptive manipulation. We also tested for an interaction between surface conditions and tactile manipulations, but we had no a priori expectation on the direction of this interaction, if any.

Methods

Subjects

Fifteen subjects participated in this study (9 females and 6 males, age: 26.1 SD 2.8 years, height: 173.5 SD 11.9 cm; body mass: 65.5 SD 13.9 kg). The exclusion criteria for this study were current low back pain, any neurological disorder that could affect balance and also, presence of any musculoskeletal problem in the lumbar area. Subjects were asked to sign informed consent, after being briefed and instructed about the research protocol. The protocol was approved by the ethics committee of the Faculty of Human Movement Sciences of the VU University Amsterdam.

Experimental protocol

The experiment took place in a single visit to the laboratory, during which subjects performed a total of 10 trials, each lasting 65 s. Trunk postural sway was measured while subjects were seated in two surface conditions: sitting on a rigid surface and on a surface that was unstable in the frontal plane. Four different sensory manipulations were applied: visual, vestibular, proprioceptive, and tactile. The order of the trials was randomized.

For the stable surface condition, subjects sat on a rigid flat surface. For the unstable surface condition, subjects sat on an adjustable chair, keeping the hips and knees 90° flexed and the feet supported. This seat with foot support was mounted on a rocking support (seesaw) with one degree of freedom in the frontal plane. The height of the seat was 185 mm, and the radius of curvature of the support was 240 mm. A metal bar was placed around the subject for safety reasons. If the subjects touched the bar during the trial, the trial was discarded and repeated. In every trial, subjects had to cross their arms, except for the trial with the tactile manipulation, where one hand was touching a sphere at the end of a robot arm while the other was still crossed (Fig. 1).

The visual manipulation consisted of subjects closing the eyes. During all other trials, their eyes were open. Except for the manipulation of visual information, all sensory manipulations were applied at a fixed frequency of 0.25 Hz, to facilitate the comparison between the different conditions.

For manipulation of vestibular information, galvanic vestibular stimulation (GVS) was used. A sinusoidal, mean zero, amplitude 1.5 mA, current was applied, through

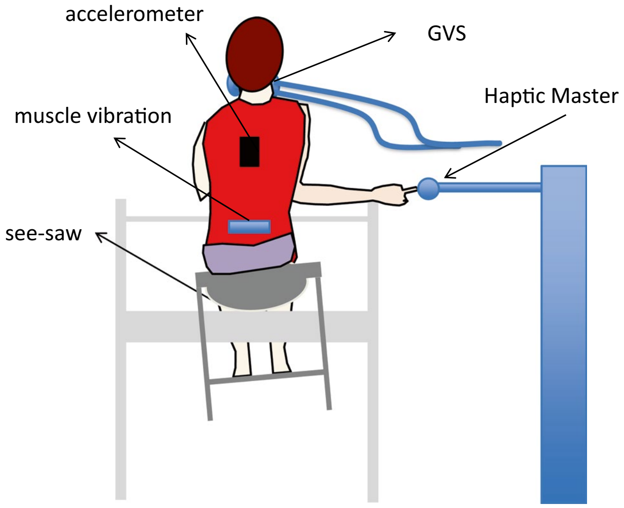

Fig. 1 Schematic illustration of the experimental setup (in the unstable surface condition)

electrodes placed over the mastoid processes, by a linear isolated stimulator (Stmisola, Biopac systems, Inc., Goleta CA, USA). GVS activates afferent fibers of the vestibular nerve and excites a wide range of vestibular neurons including the otolith system and the semicircular canals, causing an illusion that the body leans toward the cathodal side (Cohen et al. 2012), which with this stimulation protocol occurred in an alternating fashion from left to right at the stimulus frequency.

For the proprioceptive manipulation, muscle–tendon vibration (MTV) was applied over the muscle bellies of the paraspinal muscles in the mid-lumbar area. Vibration alternated between left and right paraspinal muscles, as a square wave at a fixed frequency of 0.25 Hz, applied by a custom-made stimulator consisting of two electromotors (Graphite Brushes S2326.946, Maxon, Sachseln, Switzerland) driven in a velocity loop at 100 Hz (4-Q-DC Servo Control LSC 30/2, Maxon, Sachseln, Switzerland). Muscle vibration activates mainly Ia-afferents, which causes illusions of lengthening and reflex responses to counteract the perceived movement (Goodwin et al. 1972; Roll et al. 1989).

For the tactile perturbation, subjects were asked to touch, as lightly as possible, the head of the arm of a haptic master (Moog-FCS, Nieuw-Vennep, The Netherlands), which was to their right side, outside their field of vision and which was moving at a frequency of 0.25 Hz over a range of 5 cm. Subjects were instructed to look straight ahead and not at their arm. Touching a stationary surface reduces trunk sway (Maaswinkel et al. 2014), and it has been shown that whole body sway is coupled to the rhythm of moving surfaces when these are touched (Jeka et al. 1998; Wing et al. 2011).

Measurements and data analysis

Postural sway was measured by a hybrid inertial sensor at a sample frequency of 100 Hz (Dynaport, McRoberts, the Hague, Netherlands), placed at the back over the tenth thoracic vertebrae. The sensor recorded accelerations and angular velocities in three planes. All data analysis was performed using custom-made software in Matlab R2014a (Mathworks, Natick MA, USA). For analysis, we used acceleration data to represent trunk movement, as it is more sensitive because higher frequency components are reflected more strongly in the signal than in velocity or the position signals. Inertial sensors allow relatively noise-free measurement of acceleration, in contrast with optical methods, which measure position and obtain acceleration through double differentiation, thereby introducing considerable noise. Data recording was started after the subject had adopted an upright posture and sensory manipulations had been started. Moreover, the first 5 s of every trial was discarded, in order to eliminate transient behavior. Data were bi-directionally, low-pass filtered, with a second-order 6 Hz Butterworth filter, and subsequently the root mean square (RMS) of the ML acceleration and the power spectral density of the ML acceleration at 0.25 Hz (P25; the frequency used for the rhythmic perturbations) were calculated. The latter was determined using the Welch estimation method, using a Hamming window size of 10 s, with 5 s overlap and a 10,000-point DFT, yielding a spectral resolution of 0.01 Hz. For illustrations, the spectra were normalized to total power.

Statistics analysis

Statistical analyses were performed with SPSS 20 (IBM Software, Armonk NY, USA). Normality of the data was confirmed by visual inspection of the q–q plots and box plots of the residuals and the Shapiro–Wilk test. To test the hypotheses that surface conditions (stable and unstable) and the four sensory manipulations had interaction effects on RMS trunk acceleration, we performed three-way factorial ANOVA's, with subject as a random factor and surface condition (stable/unstable) and sensory manipulation (yes/no) as fixed factors. In case of a significant interaction effect, the effect of the sensory manipulation was tested with a paired *t* test with Bonferroni correction. The effects of each of sensory manipulations were tested separately as the intensities of the perturbations applied cannot be compared between sensory modalities.

Interactions in which the effect of the sensory manipulation indicating a larger increase in sway on the unstable surface could arise from the unstable support itself amplifying the effect of any perturbation and hence do not necessarily imply reweighting of sensory

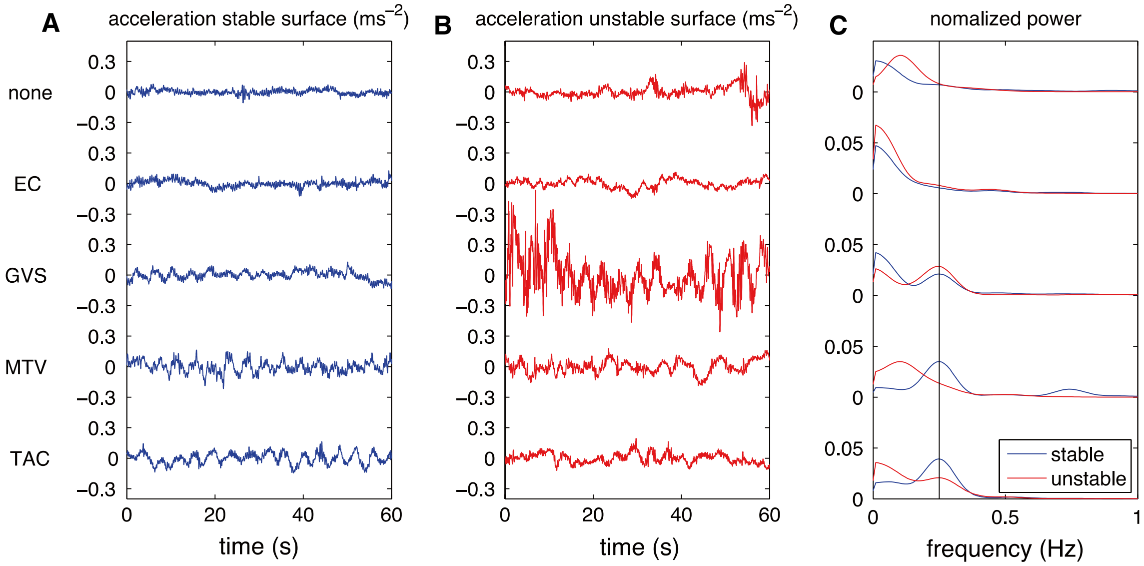

Fig. 2 Example of acceleration data of a single subject in each of the conditions. **a** Time series of acceleration on the stable surface, **b** time series of acceleration on the unstable surface, **c** normalized power spectra of the accelerations on both surfaces. *None* no sensory manipulation, *EC* eyes closed or visual manipulation, *MTV* muscle–tendon vibration or proprioceptive manipulation, *GVS* galvanic vestibular stimulation or vestibular manipulation, *TAC* tactile manipulation

Table 1 Results of four separate factorial ANOVA's on the RMS trunk accelerations, with subject as random factor and sensory manipulation and surface as fixed factors

Condition	Manipulation		Surface		Manipulation × surface	
	F	*p*	*F*	*p*	*F*	*p*
Eyes closed	**16.985**	**0.001**	**31.830**	**0.000**	**27.439**	**0.000**
Vestibular	**31.010**	**0.000**	**26.430**	**0.000**	**20.993**	**0.001**
Proprioceptive	**10.617**	**0.006**	**11.105**	**0.005**	0.022	0.884
Tactile	**12.400**	**0.004**	**15.008**	**0.002**	2.364	0.148

Significant effects are highlighted in bold

information. To circumvent this interpretation problem, two additional analyses were performed. When main effects of the sensory manipulation were present, the relative change in RMS due to the sensory manipulation was compared between surface conditions with paired *t* tests, thus correcting for effects of changes in the dynamics of the controlled system. In addition, for the rhythmic perturbations, factorial ANOVA's were performed on the P25 values. As for the RMS, significant interaction effects were followed up by *t* tests with Bonferroni correction for sensory manipulation within each surface condition. For all tests, results were considered significant at $p < 0.05$.

Results

Due to technical problems, one subject did not perform one trial with VTS. In addition, we excluded data from another subject for the eyes closed on stable support surface condition, in view of exceptionally high acceleration values of which the origin was unclear.

The acceleration data in Fig. 2 show that trunk sway was generally more pronounced on the unstable support. Moreover, it can be seen that the sensory manipulations tended to increase sway differently between the support surface conditions, with clear rhythmic responses in trunk sway identifiable in the time series (Fig. 2a, b) as well as in the normalized power spectra (Fig. 2c). Note also that the signals in the unperturbed and eyes closed conditions contain very little power at 0.25 Hz. In general, the unstable support condition caused a higher RMS acceleration (Table 1), while P25 showed this main effect only in the ANOVA for the GVS (Table 2).

Closing the eyes caused a significant increase in trunk acceleration, while an interaction with support surface was also found (Table 1; Fig. 3a). The increase in RMS was significant only in the unstable support condition ($p < 0.001$),

Table 2 Results of three separate factorial ANOVA's on power spectral density of trunk acceleration at 0.25 Hz, with subject as random factor and sensory manipulation and surface as fixed factors

Condition	Manipulation		Surface		Manipulation × surface	
	F	*p*	*F*	*p*	*F*	*p*
Vestibular	**7.527**	**0.017**	**6.590**	**0.023**	**6.033**	**0.029**
Proprioceptive	**19.249**	**0.001**	2.414	0.144	2.861	0.115
Tactile	**10.903**	**0.006**	1.501	0.242	2.056	0.175

Significant effects are highlighted in bold

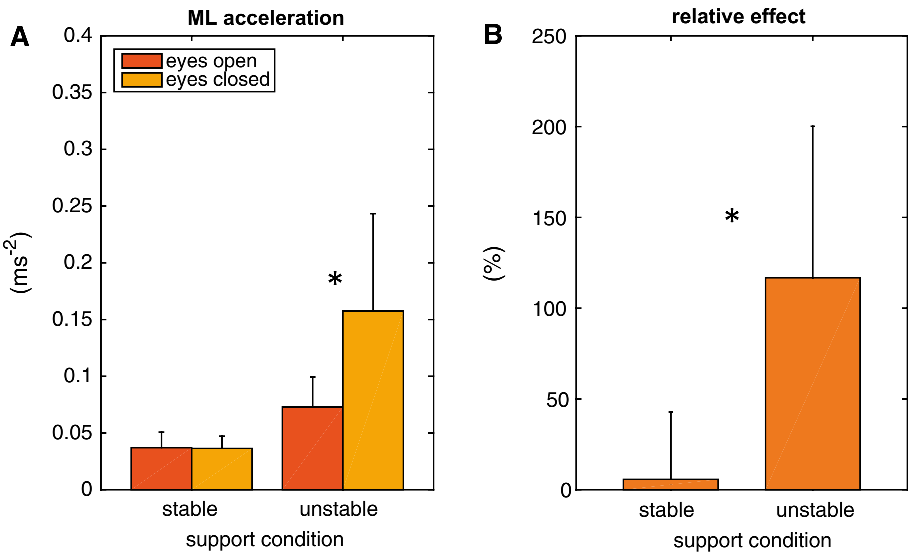

Fig. 3 Mean values of the RMS of mediolateral trunk acceleration (**a**) for the eyes and eyes closed conditions at both support surfaces, as well as the relative effects on RMS of the eyes closed compared to eyes open condition on both support surfaces (**b**). *Error bars* indicate one standard deviation and *asterisks* indicate significant effects paired *t* tests

and the relative increase in the RMS was significantly larger in the unstable condition than in the stable condition ($p = 0.008$; Fig. 3b).

GVS caused a significant increase in RMS and interacted with the surface conditions (Table 1). The increase in RMS was clearly larger on the unstable than on the stable support (Fig. 4a), but still it was significant in the stable ($p = 0.032$) and unstable condition ($p < 0.001$; Fig. 4). The relative effect of GVS on the RMS was significantly larger on the unstable than the stable condition ($p = 0.009$; Fig. 4b). A similar pattern of effects as for the RMS was observed for the power spectral density at 0.25 Hz specifically (Table 2, Fig. 4c).

While the proprioceptive manipulation significantly increased the RMS and P25 values, there were no interactions with the surface condition (Tables 1 and 2), even though the effect on RMS and P25 appeared more pronounced at the stable support surface (Fig. 5c). In line with this, the relative effect of MTV on the RMS acceleration was not different between support conditions ($p = 0.257$, Fig. 5b).

Touching the moving arm of the haptic master increased RMS and P25 acceleration. Although for both variables a tendency was observed toward smaller effects of touching the haptic master on the unstable support, there were no significant interactions between the tactile manipulation and the support conditions (Tables 1, 2; Fig. 6a, c). Similarly, for the relative effects on the RMS, only a trend toward a larger relative effect on the stable support was found ($p = 0.062$; Fig. 6b).

Discussion

The purpose of the present study was to examine the effect of sensory manipulations on trunk control during stable and unstable sitting. We hypothesized interaction effects between surface conditions and the sensory manipulations, reflecting larger effects of visual and vestibular manipulations on an unstable surface than on a stable surface and a reduced effect of proprioceptive manipulation. We also tested for an interaction between surface conditions and tactile manipulations. The results showed the expected interactions for the visual and vestibular manipulations with the surface conditions, but not for the proprioceptive and tactile manipulations.

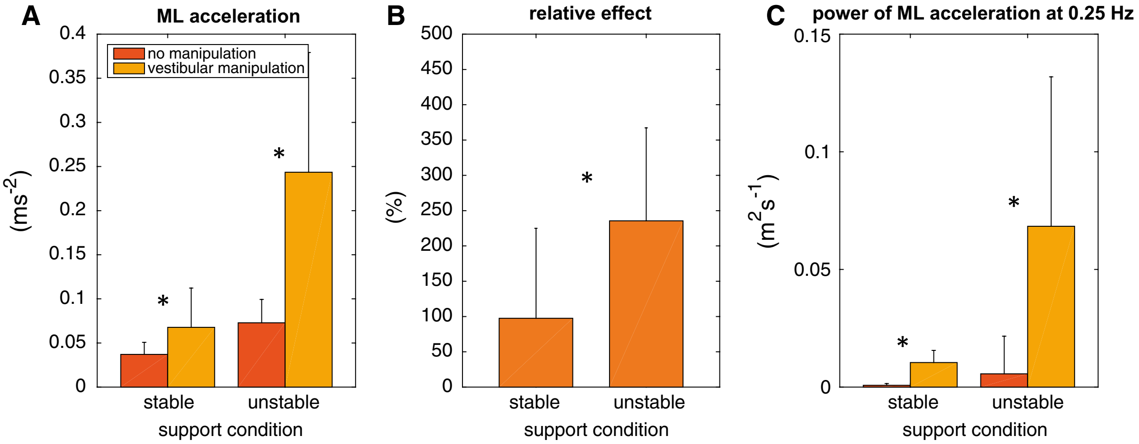

Fig. 4 Mean values of the RMS of mediolateral trunk acceleration (**a**) for the conditions with and without GVS at both support surfaces and the relative effects on RMS of the GVS compared to no GVS condition on both support surfaces (**b**), as well as mean values of power spectral density of mediolateral trunk acceleration at 0.25 Hz (**c**). *Error bars* indicate one standard deviation and *asterisks* indicate significant effects paired *t* tests

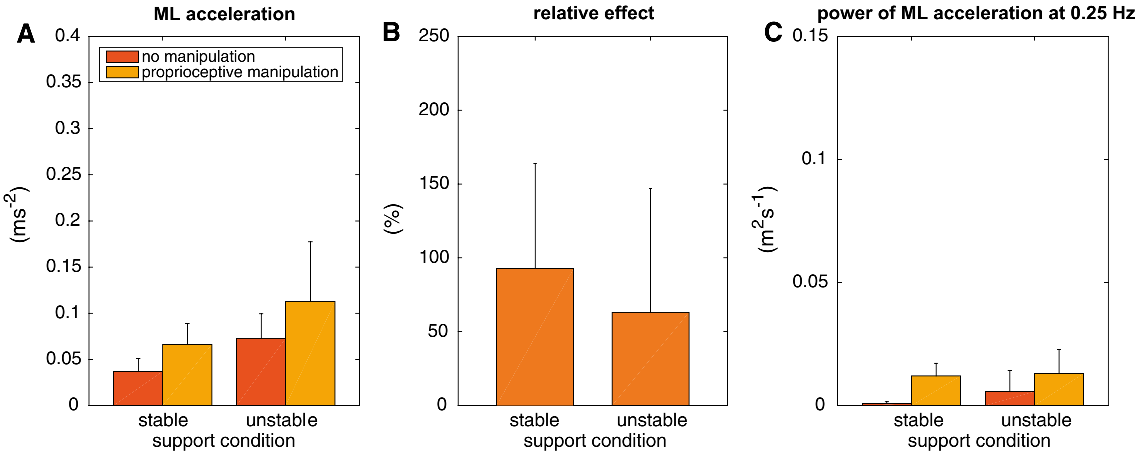

Fig. 5 Mean values of the RMS of mediolateral trunk acceleration (**a**) for the conditions with and without MTV at both support surfaces and the relative effects on RMS of the MTV compared to no MTV condition on both support surfaces (**b**), as well as mean values of power spectral density of mediolateral trunk acceleration at 0.25 Hz (**c**). *Error bars* indicate one standard deviation

When comparing the surface conditions, the unstable condition led to an increase in postural sway. Increased sway due to surface instability is not surprising and has previously been reported (Cholewicki et al. 2000; Radebold et al. 2001; Silfies et al. 2003; Reeves et al. 2006; Slota et al. 2008). The current study adds to this that changes in stability of the surface interact with manipulations of visual and vestibular information, suggesting reweighting of these sensory modalities in control of trunk posture. Such reweighting of sensory systems should be considered in research and clinical practice when aiming to assess or train trunk control and, for example, raises questions regarding the use of unstable surfaces for so-called proprioceptive training (c.f. Kiers et al. 2012).

When vision was occluded in the stable condition, ML trunk acceleration did not significantly increase. Similarly, Maaswinkel et al. (2014) did not find an effect of closing the eyes on anteroposterior trunk sway in stable sitting. These findings contrast with effects of closing the eyes on postural sway observed in many previous studies (for an overview see Mazaheri et al. 2013). Possibly, this is attributable to the smaller effect of sway angle on head movement in sitting compared to standing. In the present study, ML sway did increase with closing the eyes in the unstable condition. In line with this, Silfies et al. (2003) showed that chair movement in unstable sitting increased faster with seat instability when visual input was lacking. However, this effect was significant only for anteroposterior sway and total path length

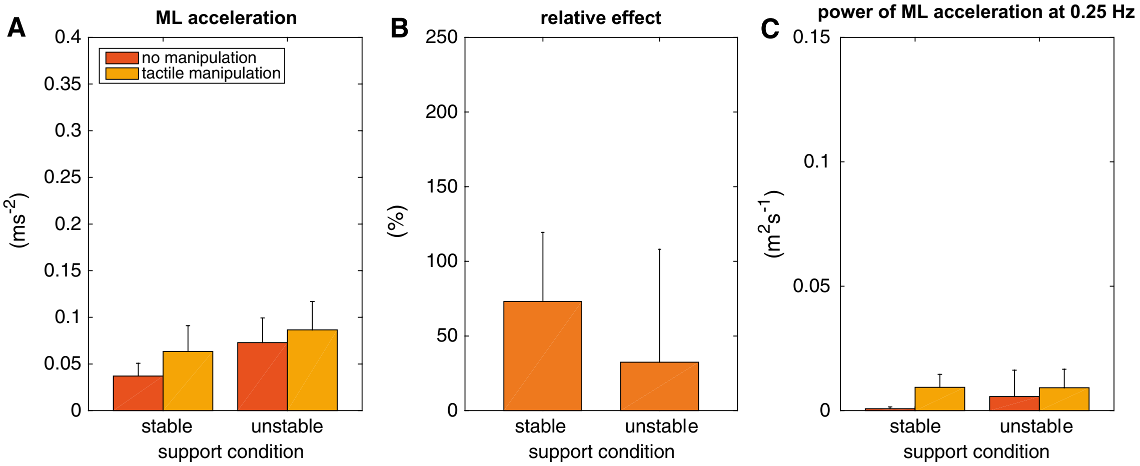

Fig. 6 Mean values of the RMS of mediolateral trunk acceleration (**a**) for the conditions with and without touching the haptic master at both support surfaces and the relative effects on RMS of the tactile manipulation compared to no tactile manipulation condition on both support surfaces (**b**), as well as mean values of power spectral density of mediolateral trunk acceleration at 0.25 Hz (**c**). *Error bars* indicate one standard deviation

and not for ML sway. Goodworth and Peterka (2009) did not find a significant effect of closing the eyes in ML sway in standing on an actively tilting platform. On the other hand, tilting the visual environment did increase sway. Combined, these data may suggest that the use of visual information in control of trunk sway is dependent on the amplitude of the visual stimulus and hence of trunk sway, which would also explain the interaction effect with surface condition found in the present study.

As expected, there was an interaction between vestibular manipulation and surface condition; relative effects and P25 were higher on the unstable surface than on the stable one. These results are in line with Fitzpatrick et al. (1994) who applied GVS while standing and found a larger EMG response in the lower leg muscles while standing on an unstable, compared to a stable surface. As for visual manipulation, the increased effect of vestibular manipulation could be due to increased reliance on vestibular inputs with increased movement amplitudes. This is in line with upweighting of vestibular information with increasing movement amplitudes, as predicted by models of sensory weighting (Maurer et al. 2006; van der Kooij and Peterka 2011) and empirically supported by data on ML trunk sway (Goodworth and Peterka 2009).

A significant increase in sway was observed also with muscle vibration on both surfaces, but absolute and relative effects on acceleration were not different between support conditions. We had hypothesized a smaller effect of the proprioceptive manipulation on the unstable surface than on the stable surface, in line with reduced effects of calf muscle vibration on unstable surfaces (Ivanenko et al. 1999; Kiers et al. 2012). On the unstable surface, proprioceptive information is ambiguously related to trunk orientation in space, which makes this input less pertinent and could even lead to responses that further offset balance. However, although some models of sensory reweighting assume that weighting of a specific input is dependent on discrepancies with a veridical signal (Mahboobin et al. 2009), other models suggest that it is based on the signal's variability (van der Kooij and Peterka 2011) or on its amplitude in relation to a sensory threshold (Maurer et al. 2006). While such weighting processes could account for upweighting of sensory channels in an absolute sense at increasing amplitudes without downweighting of 'competing' channels, these models assume a reciprocal weighting to avoid changes in the overall feedback gain. The present data suggest that the relative but not the absolute weight of proprioceptive information decreased on the unstable surface, since the effects of visual and vestibular input increased, while that of proprioceptive input remained constant. While this is in line with a shift toward reliance on vestibular and visual information as movement amplitudes increase (Goodworth and Peterka 2009; Polastri et al. 2012; Asslander and Peterka 2014), it does not support the reciprocal nature of sensory reweighting. Polastri et al. (2012) likewise reported an asymmetric change in weighting of visual and proprioceptive information, which was however not supported by data presented by Assländer and Peterka (2014). It should be noted here that other sensory modalities may play a role. Sensing the ground reaction force through pressure sensors in the skin can potentially contribute to trunk control in the present task (c.f. Maurer et al. 2006). This source of information is greatly attenuated on the unstable surface and since it is not known whether and how its weighting changes, the reciprocal nature of weighting of all relevant sensory modalities cannot be excluded.

The tactile manipulation also caused an increase in sway in all the trials and did not interact with surface condition, although a tendency toward smaller effects was found in the unstable condition. Several studies have shown that light touch can reduce postural sway in the ML direction in standing whether the eyes are open or closed (Jeka and Lackner 1994; Holden et al. 1994). Also light finger touch with a moving object leads to entrainment of the whole body to the movement frequency of the object (Jeka et al. 1997, 1998). While it has previously been shown that tactile information has a strong influence on trunk sway, irrespective of the body part that is in contact with an external object (Maaswinkel et al. 2014), this study adds that also the effect of touching a moving object generalizes to control of trunk posture in sitting.

Some limitations of the current study need to be addressed. Most importantly, the strength of the different manipulations applied was not scaled, rendering direct comparisons of the effects of these sensory manipulations impossible. Secondly, with the change in surface conditions, the dynamics of the controlled system changed. Hence, increased responses to sensory manipulations cannot directly be attributed to upweighting of sensory information. Therefore, we also compared relative effects within surface conditions. Consistent increases in both relative and absolute effects are suggestive though no definitive proof of upweighting of the sensory information manipulated. Finally, the subjects that participated in this study consisted of young healthy individuals; consequently, the results cannot be generalized to clinical populations in which trunk control is affected such as low back pain (e.g. Radebold et al. 2001) or Parkinson's Disease (van der Burg et al. 2006). Further study in patient populations could reveal differences in the use of sensory information in such tasks compared to healthy controls (c.f. Claeys et al. 2011; Willigenburg et al. 2013).

Conclusion

The aim of the present study was to investigate the effect of sensory manipulations on trunk control on stable and unstable sitting. Interactions between surface condition and the manipulation of visual and vestibular information were found, with stronger effects of these manipulations on the unstable surface. The effects of muscle vibration to manipulate proprioceptive information and of touching a slowly moving object were constant between the two surface conditions. These findings suggest a relative upweighting of visual and vestibular information compared to proprioceptive and tactile information in trunk control on an unstable surface.

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Conflict of interest The authors declare that they have no conflict of interest.

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