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Can explicit visual feedback of postural sway efface the effects of sensory manipulations on mediolateral balance performance?

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[1]*MOVE Research Institute Amsterdam, Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands;* [2]*Department of Medicine, Royal Melbourne Hospital, The University of Melbourne, Melbourne, Australia;* [3]*College of Osteopathic Medicine, Michigan State University, East Lansing, Michigan; and* [4]*Musculoskeletal Research Unit, Department of Rehabilitation Sciences, Faculty of Kinesiology and Rehabilitation Sciences, Katholieke Universiteit Leuven, Leuven, Belgium*

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Cofré Lizama LE, Pijnappels M, Reeves NP, Verschueren SM, van Dieën JH. Can explicit visual feedback of postural sway efface the effects of sensory manipulations on mediolateral balance performance? *J Neurophysiol* 115: 907–914, 2016. First published December 2, 2015; doi:10.1152/jn.00103.2014.—Explicit visual feedback on postural sway is often used in balance assessment and training. However, up-weighting of visual information may mask impairments of other sensory systems. We therefore aimed to determine whether the effects of somatosensory, vestibular, and proprioceptive manipulations on mediolateral balance are reduced by explicit visual feedback on mediolateral sway of the body center of mass and by the presence of visual information. We manipulated sensory inputs of the somatosensory system by transcutaneous electric nerve stimulation on the feet soles (TENS) of the vestibular system by galvanic vestibular stimulation (GVS) and of the proprioceptive system by muscle-tendon vibration (VMS) of hip abductors. The effects of these manipulations on mediolateral sway were compared with a control condition without manipulation under three visual conditions: explicit feedback of sway of the body center of mass (FB), eyes open (EO), and eyes closed (EC). Mediolateral sway was quantified as the sum of energies in the power spectrum and as the energy at the dominant frequencies in each of the manipulation signals. Repeated-measures ANOVAs were used to test effects of each of the sensory manipulations, of visual conditions and their interaction. Overall, sensory manipulations increased body sway compared with the control conditions. Absence of normal visual information had no effect on sway, while explicit feedback reduced sway. Furthermore, interactions of visual information and sensory manipulation were found at specific dominant frequencies for GVS and VMS, with explicit feedback reducing the effects of the manipulations but not effacing these.

sway; posture; sensory weighting; balance

BALANCE IN AN UPRIGHT POSTURE is controlled by feedback based on visual, vestibular, proprioceptive (mainly from muscle spindles), and exteroceptive (in particular from cutaneous receptors in the soles of the feet) information (Kennedy and Inglis 2002; Oie et al. 2002; Peterka 2002; Roll et al. 2002; Thompson et al. 2011). However, the availability and reliability of these sensory inputs can be affected by intrinsic and environmental changes, which require flexibility and adaptation of the balance control system (Bingham et al. 2011; Goodworth et al. 2014; Goodworth and Peterka 2010; Mahboobin et al. 2009; Peterka and Loughlin 2004). This flexibility is achieved by reweighting sensory inputs based on reliability and pertinence to balance control in a given situation. For example, proprioceptive input from muscle spindles in the calf muscles contains limited information on orientation relative to vertical when a body is standing on a compliant foam surface. In this situation, the effects of manipulations of spindle inputs have been shown to be reduced compared with standing on a rigid surface (Kiers et al. 2012). Similarly, vestibulospinal reflex gains are higher when visual inputs and tactile information are not available to the balance control system (Welgampola and Colebatch 2001).

Sensory reweighting has been studied mainly by decreasing pertinence or reliability of information in one of the sensory channels involved in balance control. The effect of explicit feedback on balance has received less attention, although it is known that explicit visual feedback on balance decreases postural sway in healthy and patient populations (Kennedy et al. 2013; Rougier 2003). Augmented feedback differs from visual feedback normally used in balance control in that direct information on, for example, the position of the center of mass (CoM) of the body is provided, whereas visual feedback under normal circumstances comprises indirect information on head orientation and movement. Potentially, the availability of such explicit visual information leads to down-weighting of other, less unambiguous, sensory information. This would have clinical relevance, as explicit visual feedback on balance is currently used in diagnostic tests and training and rehabilitation programs for balance control (Cofre Lizama et al. 2014; Zijlstra et al. 2010). If down-weighting of other sensory modalities occurs, impairments in these systems might be overlooked in diagnostic tests and training may be suboptimal. Despite the fact that studies have explored the effects of sensory manipulations and explicit visual feedback on balance control and despite the fact that studies have addressed reweighting of visual, vestibular, and proprioceptive information, to our knowledge, the interaction of explicit feedback with these other sensory modalities has not been addressed (Hay et al. 1996; Mazaheri et al. 2013; Oie et al. 2002; Zijlstra et al. 2010). Therefore, a better understanding of the interaction of explicit visual feedback and sensory impairments is necessary not only to get better insight into the underlying mechanism of balance control but also to

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give implications for the development of clinical tools for balance assessment and training.

Current literature on sensory reweighting has shown that the nervous system adjusts the gain of the different input sources under pathological (i.e., vestibular loss) (Horak 2009), experimental (Peterka and Loughlin 2004) and environmental conditions (Goodworth et al. 2014) that disturb or efface sensory information. On the other hand, the effects of enhancement of sensory inputs have been explored, as a means to counteract impairments of balance control. This was mainly done by increasing somatosensory information from the feet sole using texturized and vibrating insoles and showed positive effects on balance (Palluel et al. 2009; Priplata et al. 2003) suggesting that sensory impairments in other systems may be overcome by augmented feedback from the foot sole receptors. Similarly, it is possible that the use of visual feedback can compensate for other sensory deficits. However, sensory reweighting under augmented visual feedback has to our knowledge not been studied.

Mediolateral (ML) balance is of particular interest, since it is more affected by ageing and disease and since its deterioration has been associated with an increased risk of falling (Brauer et al. 2000; Hilliard et al. 2008; Maki et al. 1994; Maki and McIlroy 1996; Melzer et al. 2010). Therefore, this study will focus on balance performance in the frontal plane, and the effects of nonexplicit (normal visual information) and explicit feedback on CoM sway under sensory manipulation conditions. Since CoM is the variable to be controlled by the balance control system (Winter et al. 1990) and there is a linear relationship between CoM and CoP when the body is standing, CoM feedback is more intuitive than CoP feedback.

The aim of this study was to determine whether the effects of vestibular, proprioceptive, and somatosensory manipulations are reduced by the presence of visual information and by explicit feedback on body CoM sway. We hypothesized that manipulation of sensory systems increases mediolateral CoM sway but that this effect is reduced by the presence of visual information and even more by explicit feedback on CoM sway.

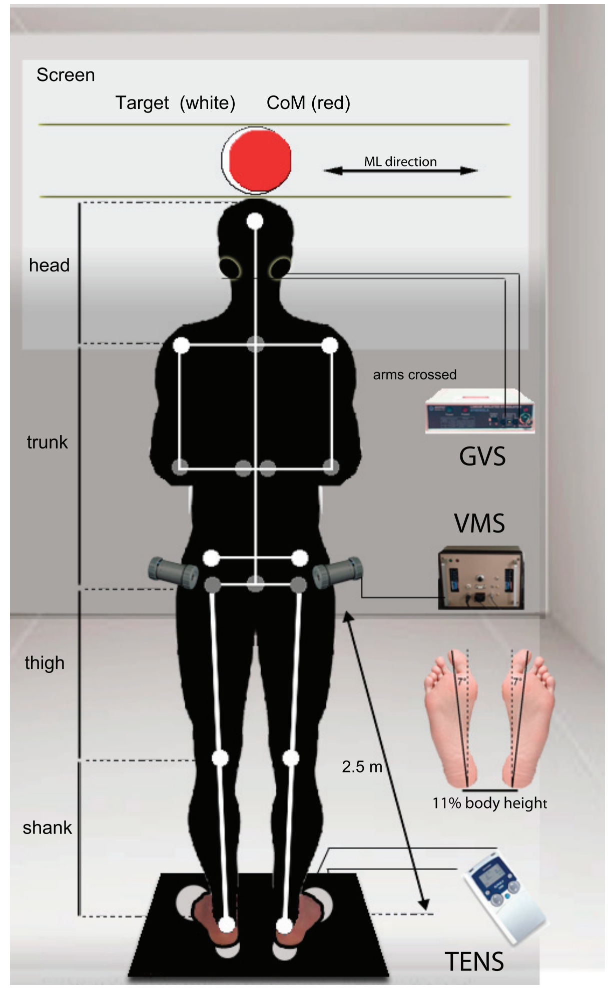

Fig. 1. Illustration of the setup and the model for center of mass (CoM) calculation utilized in this experiment, showing a silhouette of a subject with marker placement superimposed (in white actual makers and in grey estimated joint centers) and the display of the CoM feedback (red sphere). The white sphere in the center represents a static target placed in the middle of the screen. The allocation of galvanic vestibular stimulation (GVS) electrodes (mastoid processes), muscle-tendon vibration (VMS) vibrators (half way between iliac crests and major trochanters), and transcutaneous electric nerve stimulation on the feet soles (TENS) electrodes (grey areas below the feet) are also depicted. An insertion of foot soles is presented showing foot positioning during the experiments (stance width and angle).

METHODS

Subjects. Nineteen healthy young adults, 12 women and 7 men, participated in this study (age: 28 ± 3 yr; height: 1.75 ± 0.10 m; and weight: 70.0 ± 8.0 kg). Participants did not report any musculoskeletal or neurological conditions that could affect balance. This research was approved by the local Ethical Committee, in accordance with the ethical standards of the Declaration of Helsinki. All subjects were informed of the experimental procedures and signed an informed consent form before the experiment.

Task and procedure. Each participant performed a series of standing tasks of 50-s long, each while barefoot and with the arms crossed on the chest. CoM data were obtained using a nine-marker, two-dimensional kinematic model. Markers were located at the forehead, mid-shoulders, anterior-superior iliac spines (ASIS), mid-knees and mid-ankles, and three-dimensional (3D) marker coordinates were captured with an Optotrak Certus motion capture system (Northern Digital Instruments, Canada). The accuracy of this system is 0.1 mm with a resolution of 0.01 mm. Gender-specific CoM calculations were performed using scaling of anthropometric data and of inertial parameters described by de Leva (de Leva 1996). For setup and model details refer to Fig. 1. 3D marker trajectories were streamed into D-flow 3.10.0 software (Motek Medical), which was used to calculate, display, and record (60 samples/s) CoM ML displacements (9-cm diameter red sphere), as well as to produce a stationary target (11-cm diameter white sphere) in the middle of a screen located 2.5 m in front of the participants. The delay of the system was calculated to be 16 ms, which is equivalent to one sample.

Displacement of the CoM in the frontal plane when standing still was measured under three conditions: eyes open with explicit visual feedback (FB) on ML body CoM sway, eyes open (EO) without explicit feedback, and eyes closed (EC). During all conditions the room was dimly lit. In the eyes open condition, the subject was instructed to look at the white dot projected on the screen, while the peripheral visual field offered some structured information in that three walls, a table, and door were visible. Each of these conditions was measured three times for 50 s. These conditions were also measured under three types of sensory manipulations: somatosensory, vestibular, and proprioceptive. Hence, in total, each condition × manipulation was assessed during 150 s.

For the somatosensory manipulation, we used a transcutaneous electric nerve stimulator (TENS; ElphaII 3000, Danmeter, Denmark) to apply a current to the feet soles through an aluminum plate under the feet. The stimuli were delivered with the current flow alternating from left foot to right foot at 0.25 Hz (ramp up: 0.5 s; plateau: 1 s; and ramp down: 0.5 s). Each 2-s block consisted of 120 pulses/s with a maximum current of 18-mA intensity and pulse width of 200 μs. TENS parameters of 80–140 pulses/s with a 200-μs pulse width are commonly used for sensory stimulation (Watson 2008). In addition, pilot experiments showed that with these parameters stimuli were above sensitivity and below muscle contraction thresholds when applied to the feet sole. For the vestibular manipulation, we used a linear isolated stimulator (Stmisola; Biopac Systems) to produce galvanic vestibular stimulation (GVS) with a maximum intensity of 1.5 mA. Maximum intensity was selected based on previous research showing that it evokes balance responses with minor adverse effects (Fitzpatrick and Day 2004; Utz et al. 2011). Flexible carbon electrodes (5 $\times$ 5 cm) were placed on the mastoid region using conductive gel and tape for fixation. Finally, for the proprioceptive manipulation, we used vibratory muscle-tendon stimulation (VMS) and attached a pair of custom-made vibrators bilaterally over the gluteus-medius topographic region. These muscles were selected since they are the main actuators involved in maintaining upright stance in the frontal plane (Bingham et al. 2011; Salavati et al. 2007; Winter et al. 1996). A vibration frequency of 100 Hz was selected to maximize effects on postural sway (Roll et al. 1989; Wierzbicka et al. 1998). For GVS current flow direction and VMS body side stimulated, we constructed a left/right alternating pattern as the sum of six sine waves (0.15, 0.25, 0.35, 0.45, 0.55, and 0.65 Hz). For the GVS, all signal peaks were scaled to 1.5 mA to avoid adverse effects (Utz et al. 2011). For the VMS, peaks were transformed to square-waves of 4 V, which corresponded with 100 Hz. Due to these transformations, both signals contained multiple frequencies with most power at 0.45, 0.55 and 0.65 Hz (Fig. 2).

In total, each participant performed 36 trials (3 conditions $\times$ 4 manipulations $\times$ 3 repetitions). Subjects were given at least 1-min rest in between trials and did not report fatigue between trials or at the end of the session. A modified 10-point Borg scale (Mahler et al. 1987) was used to quantify the perceived exertion, when reaching a score of 4 (somewhat hard) subjects were enforced to take longer rests periods until perceived exertion was below 3 (moderate).

Data analysis. The ML CoM sway power spectrum was calculated using a 1,200-point Fourier transform with zero-padding as needed to obtain a 0.05-Hz resolution. The sum of the total energy over the spectrum was used as a measure of the overall CoM sway. In addition, energy at the dominant frequencies in the manipulation signals was determined (TENS = 0.25 Hz and for GVS and VMS = 0.45, 0.55, and 0.65 Hz).

Statistical analysis. Repeated measures two-way ANOVAs were used to determine the effect of sensory manipulations, visual conditions, and their interaction on the total energy and on the energy at each of the dominant frequencies in the manipulations signals. Descriptive statistics were performed to determine the direction of the differences.

RESULTS

Figure 2 shows a typical example of the ML sway of one subject under each of the experimental conditions. As can be seen, ML CoM sway was reduced when providing visual FB but no obvious differences are visible between the EO and EC conditions. The shape of the sensory manipulation signals (TENS, GVS, and VMS) is also shown. The positive values in this figure indicate right side stimulation and CoM displacement, whereas negative values indicate the same but to the left. Averaged CoM sway for the control condition, TENS, GVS, and VMS at the three visual input conditions (FB, EO, and EC) is presented in Fig. 3. Table 1 presents the means and results of statistical tests for total sway energy, whereas Tables 2 and 3

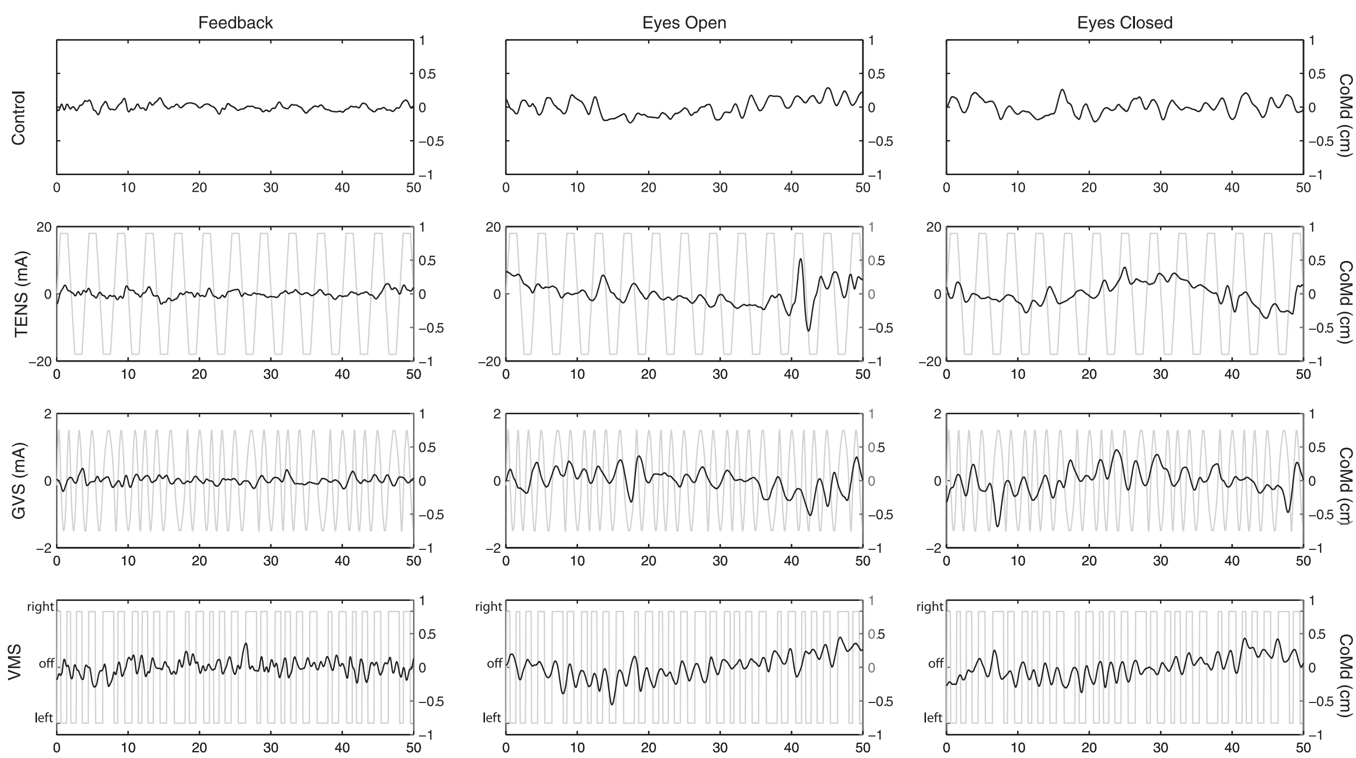

Fig. 2. From *top* to *bottom* plots represent the CoM mediolateral (ML) sway (black lines) of a representative subject in the control condition and with TENS, GVS, and VMS manipulations and, from left to right, in feedback, eyes open, eyes closed conditions. The labels on the left-y-axes refer to the experimental conditions and the input signal (if applicable). The grey lines represent the shapes of the TENS (mA), GVS (mA), and VMS (on/off) signals. The positive values indicate right side stimulation (left axis) and CoM displacement (right axis) where negative values indicate displacement to the left.

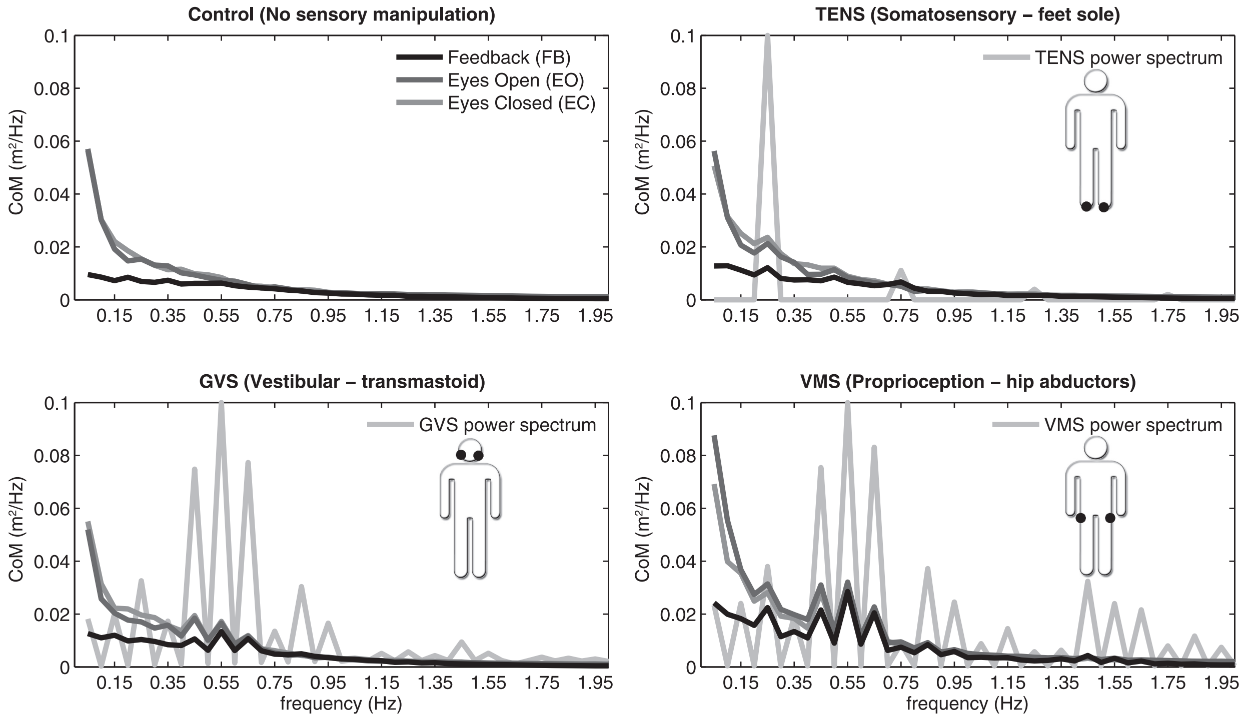

Fig. 3. The averaged ML CoM power spectrum curves under the 3 visual conditions in separate plots for each of the sensory manipulations (Control, TENS, GVS, and VMS). The vertical axis shows absolute values of energy calculated for the CoM-ML displacement for each of the frequencies in the 0.05- to 2.0-Hz range. The lightest grey curve in the TENS, GVS, and VMS plots shows the power spectrum curve for the sensory manipulations signal.

present the descriptive and statistical tests results for the energy at each of the manipulations' dominant frequencies. Overall, sensory manipulations tended to increase the means of all variables analyzed compared with control conditions. Also, visual input had clear effects on sway energy, with the FB condition exhibiting lower values than EO and EC conditions across all sensory manipulations, yet only few differences were found between EO and EC conditions.

Manipulation of sensory information from the feet soles (TENS). In comparison to the control condition, TENS did not significantly increase the total sway energy (Table 1). A significant effect of visual input was found, with contrasts indicating lower energy in the FB condition. No interaction of visual condition and TENS was found. The effect of TENS on the sway energy at 0.25 Hz was significant, while the effect of visual input was borderline significant and no interaction effect was found (Table 3).

Manipulation of vestibular information (GVS). In comparison to the control condition, GVS significantly increased sway energy over the whole spectrum (Table 1), as well as at each of the dominant frequencies (Table 2). Also significant effects of visual input were found for the whole power spectrum and at each of the dominant frequencies except at 0.65 Hz, with contrasts indicating lower energy in the FB condition. Interaction effects of GVS and visual conditions were found at 0.45 and 0.55 Hz, with smaller effects of GVS in the FB than EC and EO conditions (Table 4) but not at 0.65 Hz (Tables 3 and 4).

Manipulation of proprioceptive information (VMS). A significant effect of VMS was found for the total energy (Table 1) and for energy at each of the dominant frequencies (Table 2). In addition, significant main effects of visual input were found, with contrasts indicating lower values when explicit visual feedback was available. Significant interaction effect was found for total energy and at 0.45 Hz. These interaction indicated a smaller effect of VMS in the FB condition (Tables 3 and 4), but in contrast with our hypotheses, VMS had a stronger effect with EO than with EC, which was significant when considering the total energy.

Table 1. *Descriptive statisticsfor the sum of energy across all frequencies analyzed for each sensory manipulation and visual input condition*

	Feedback		Eyes Open		Eyes Closed				
	Mean	SD	Mean	SD	Mean	SD	Manipulation	Visual Input	Manipulation × Visual Input
Control	0.132	0.038	0.268	0.086	0.274	0.074			
TENS	0.165	0.065	0.286	0.098	0.302	0.124	0.121	<.001*	0.798
GVS	0.185	0.049	0.303	0.097	0.335	0.108	0.002*	<.001*	0.658
VMS	0.310	0.103	0.523	0.114	0.458	0.128	<.001*	<.001*	0.046*

Descriptive statistics (mean ± SD) for the sum of energy across all frequencies analyzed (0.05–2.0 Hz) for each sensory manipulation and visual input condition (feedback, eyes open, and closed). *Right side*: *P* values for the repeated-measures (RM)-ANOVAs using each manipulation [transcutaneous electric nerve stimulation on the feet soles (TENS), galvanic vestibular stimulation (GVS), or muscle-tendon vibration (VMS)] and visual condition (feedback, eyes open, and closed) as factors. *Significant effects.

Table 2. *Results of the RM-ANOVAs on the energy at the dominant frequencies for each of the manipulations and visual condition*

	TENS			GVS			VMS		
Frequency, Hz	Man.	Vis. Input	Man. × Vis. Input	Man.	Vis. Input	Man. × Vis. Input	Man.	Vis. Input	Man. × Vis. Input
0.25	0.033*	0.070	0.224	—	—	—	—	—	—
0.45	—	—	—	0.001*	0.003*	0.011*	<0.001*	0.002	0.033
0.55	—	—	—	<0.001*	0.007*	0.024*	<0.001*	0.145	0.175
0.65	—	—	—	<0.001*	0.697	0.534	<0.001*	0.756	0.580

Results of the RM-ANOVAs on the energy at the dominant frequencies for each of the manipulations (TENS: 0.25 Hz; GVS and VMS: 0.45, 0.55, and 0.65 Hz) and visual condition (feedback, eyes open and closed) as factors. Man., manipulation; Vis. Input, visual input. *Significant effects.

DISCUSSION

This study aimed to determine whether the presence of visual information and explicit feedback of body CoM sway reduce the effects of somatosensory, vestibular, and proprioceptive manipulations on CoM sway. We showed that somatosensory, vestibular, and proprioceptive manipulations led to increased body CoM sway. Absence of normal visual information had no significant effect on ML CoM sway, while explicit feedback on body CoM reduced ML sway. Visual feedback on CoM position did attenuate effects of vestibular and proprioceptive manipulations on ML sway but did not efface the effects of any of the sensory manipulations.

Sensory manipulations. To our knowledge, this was the first study using TENS to disturb somatosensory inputs from the foot sole receptors during standing. The main effect of TENS is the depolarization of Aβ (II) somatosensory fibers, present in pressure receptors (Merkel discs) in the foot sole (Dickstein et al. 2006; Shaffer and Harrison 2007). Similar to previous studies that have used other somatosensory manipulations, such as cooling (Billot et al. 2013; Stal et al. 2003), percutaneous stimulation (Thomas and Bent 2013), and vibration (Thompson et al. 2011), TENS also increased postural sway, highlighting the importance of foot sole receptors for balance. Application of TENS bilaterally to the posterior aspect of the leg and below the sensory threshold has been shown to reduce postural sway (Dickstein et al. 2006). Since we switched the TENS signal from left foot to right foot at 0.25 Hz with a fixed, suprathreshold 18-mA intensity, we expected an opposite effect. This effect was reflected in COM sway at 0.25 Hz, for which a significant increase with TENS was found. Nevertheless, no significant effects were found for total sway energy, which indicates an overall limited and quite specific effect of the stimulation on body CoM sway. The lack of significant findings can be also explained by the lower complexity of the TENS stimulation signal (compared to GVS and VMS), to which the balance control system may respond in a more linear fashion. The single-frequency somatosensory stimulation may have elicited fairly simple reflexive responses only (Billot et al. 2013; Stal et al. 2003; Thomas and Bent 2013; Thompson et al. 2011). Note that for none of the subjects the selected intensity produced any visible or subjectively reported muscle contraction, which could have caused CoM sway towards the side contralateral to the stimulated foot. Although CoM sway was lower with feedback than in eyes open and closed conditions, feedback did not overcome the effects of TENS.

GVS stimulates the afferents of otholith organs as well as the semicircular canals, which elicits balance responses that incline the body towards the anodal side (Fitzpatrick and Day 2004). In our setup, the anodal side alternated from left to right, which induced sway at the frequencies contained in the GVS signal, as was previously shown for sway of the head (Forbes et al. 2013). With regards to the effect of visual input, the feedback condition exhibited the lowest energy values. Yet, even with explicit feedback, sway was still significantly larger

Table 3. *Descriptive statistics for each energy at each of the dominant frequencies in the sensory manipulation signals for all visual input conditions*

	0.25 Hz		0.45 Hz		0.55 Hz		0.65 Hz	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Control								
Feedback	0.005	0.005	0.003	0.002	0.002	0.002	0.002	0.001
Eyes open	0.012	0.008	0.006	0.005	0.003	0.002	0.002	0.001
Eyes closed	0.017	0.020	0.006	0.005	0.004	0.004	0.002	0.001
TENS								
Feedback	0.011	0.013	—	—	—	—	—	—
Eyes open	0.027	0.028	—	—	—	—	—	—
Eyes closed	0.060	0.121	—	—	—	—	—	—
GVS								
Feedback	—	—	0.008	0.006	0.011	0.009	0.007	0.006
Eyes open	—	—	0.020	0.018	0.018	0.014	0.007	0.006
Eyes closed	—	—	0.030	0.035	0.023	0.025	0.008	0.007
VMS								
Feedback	—	—	0.026	0.024	0.045	0.041	0.025	0.020
Eyes open	—	—	0.053	0.053	0.063	0.055	0.027	0.023
Eyes closed	—	—	0.044	0.042	0.057	0.052	0.026	0.023

Descriptive statistics (mean ± SD) for each energy at each of the dominant frequencies in the sensory manipulation signals (0.25 Hz for TENS and 0.45, 0.55, and 0.65 Hz for GVS and VMS) for all visual input conditions.

Table 4. *Results of the post hoc tests where interactions between manipulations and visual inputs were found for the total energy and energy at dominant frequencies*

	Effect of GVS	Effect of VMS
Total energy		
FB-EC	—	0.730
FB-EO	—	0.012*
EO-EC	—	0.042*
Energy at 0.45 Hz		
FB-EC	0.014*	0.031*
FB-EO	0.011*	0.038*
EO-EC	0.054	0.190
Energy at 0.55 Hz		
FB-EC	0.016*	—
FB-EO	0.022*	—
EO-EC	0.231	—

Results of the post hoc tests where interactions between manipulations and visual inputs were found for the total energy and energy at dominant frequencies (FB, feedback; EO, eyes open; EC, eyes closed). *Significant differences.

with GVS than in the control condition. Possibly, responses arising from vestibulospinal reflexes may account for this, as it has been previously shown that making sensory channels available (i.e., opening the eyes), while perturbing vestibular inputs, does not completely remove short and medium latencies vestibulospinal reflexes (Welgampola and Colebatch 2001). Interactions of GVS with visual information were found at 0.45 and 0.55 Hz, indicating a reduced effect of GVS in the presence of visual feedback on balance. However, feedback did not completely efface the effect of GVS at the dominant frequencies of the manipulation signal.

VMS predominantly activates type Ia afferents of muscle spindles, which may cause reflexive muscle activation and in addition the subject perceives "lengthening" of the muscle, which may cause voluntary activation, leading to responses that increase sway at the input frequency (Roll et al. 1989; Wierzbicka et al. 1998). Invalid input may cause a decreased use (down-weighting) of the Ia-afferent input. Under the feedback condition, enhanced (vision) and nonperturbed (vestibular and somatosensory) sensory channels could theoretically compensate for the perturbed Ia afference. However, VMS resulted in larger ML sway for all visual input conditions compared with the control condition, which may reflect an inability to generate inhibitory mechanisms for reflexive responses and/or down-weighting of illusory muscle lengthening. Significantly lower energy values were observed for feedback compared with eyes open and closed conditions, with interactions of vision and VMS observed at 0.45 Hz and for total sway energy. Contrast analyses for these interactions revealed that differences occurred between feedback and eyes closed and between feedback and eyes open for the 0.45 Hz and between eyes open and closed for the total energy. The interaction at 0.45 Hz is in line with down-weighting of proprioceptive information with visual feedback. Less sway in the EC compared with the EO condition for total sway energy may reflect a tighter balance control called into play when proprioception is disturbed in the absence of visual inputs. A possible strategy to reach such tight control is by increasing stiffness through increased muscle coactivation of the main ML stabilizers at both sides. This is a strategy observed in the elderly while standing and during gait (Cenciarini et al. 2010; Hortobágyi et al. 2009).

Interactions with visual conditions were limited in general. However, it should be kept in mind that the manipulations applied may have had substantial amplitudes compared with the effects of balance impairments. Given the nonlinearity of the sensory system, it cannot be concluded that subtle impairments of sensory systems would not be masked by explicit visual feedback on balance control. Further studies should therefore address amplitude dependency of interactions between sensory manipulations and visual feedback.

It has been reported that not all individuals are able to take advantage of visual feedback to enhance balance control (Boudrahem and Rougier 2009) and that, to reduce postural sway, visual CoP feedback must have a gain (amplification of the actual displacement in the visual display) of at least 5 on display (Pinsault and Vuillerme 2008). In our experiment, the gain for visual display of the CoM movement ranged from 7 to 9 between subjects, due to normalization for height, which ensured noticeable movement of the CoM on the display. It is noteworthy that all subjects in this experiment decreased ML CoM sway in the frequency range analyzed when visual feedback was presented.

Visual information. Most of the literature exploring the contribution of vision to balance control manipulated visual inputs by using eyes closed conditions (Pasma et al. 2014) or by moving the visual surround (Peterka 2002). In the present study, the utilization of explicit feedback of the CoM is an artificial condition, which cannot be compared directly to the enhancement of natural perception of postural sway (Dault et al. 2003). As shown in previous studies, explicit visual feedback reduced CoM sway compared with eyes closed conditions (Boudrahem and Rougier 2009; Kennedy et al. 2013; Rougier 2003). However, no significant reduction in sway was found in the EO compared with the EC condition, demonstrating the ability of the balance control system to reweight sensory inputs (Hay et al. 1996) This also suggests a limited contribution of visual information to ML balance control under normal, bipedal standing conditions but highlights the possibility of increasing its relative contribution, as demonstrated by a significant reduction in energy across the whole power spectrum analyzed when explicit feedback was provided.

It has been shown that somatosensory (Dickstein et al. 2006) and proprioceptive (Palluel et al. 2009; Priplata et al. 2003) enhancement can increase balance control. Although Dault et al. (2003) showed that visual feedback can also improve balance, we have shown that this type of sensory enhancement is not enough to overcome the effects of sensory manipulations of other systems. Goodworth et al. (2014), using ML surface-tilt perturbations, showed that vision gain increases at narrow stance width; hence, visual feedback may increase the visual contribution to balance control in more challenging environments. However, it is noteworthy that proprioceptive manipulations using mechanical perturbations (Goodworth et al. 2014; Goodworth and Peterka 2010) may not be comparable to those used in our experiment in which balance responses are elicited by sensorial illusions (TENS, GVS, and VMS). Further studies should explore whether visual feedback may decrease the effects of mechanical perturbations (proprioceptive and somatosensory) more than the effects of individual sensory manipulations of somatosensory and proprioceptive afferents.

Unlike most experiments that use CoP to study balance, we tested ML sway of the CoM. This may explain disparities with previous studies that showed effects of closing the eyes on sway, as these measured the CoP in AP or AP and ML directions combined (Fransson et al. 2007; Nardone and Schieppati 2010). However, it is also possible that disparities with previous studies may be due to the length of the trials, which ranges across studies from 20 s to 2 min (Lafond et al. 2004; LeClair and Riach 1996). The effect of vision appears to be dependent on the amplitude of movements of the visual field (Goodworth and Peterka 2009). The ML sway in standing with a wide base of support as assessed in the present study may be too small for visual information to provide salient stimuli. In addition, the visual environment in which we tested our subjects may have provided limited information compared with conditions in previous studies, as experiments were performed in a dimly lit room and while the peripheral visual field offered some structured information in that walls, a table, and door were visible, the visual target projected consisted of a single point only.

Evidence suggests that young adults rely less on vision than older adults (Hay et al. 1996; Tanaka and Uetake 2005). In line with our findings, in young adults, vision has been estimated to account only for 10% of the sensory input used for balance control when standing (Peterka 2002). A larger contribution of vision could be expected during application of the sensory manipulations; however, differences between EO and EC conditions were not significant during TENS and GVS and actually opposite to expectations during VMS. Differences between EO and EC conditions may be exacerbated in older adults, who have been reported to rely more heavily on visual inputs (Hay et al. 1996). However, such increased visual reliance is thought to be more related to a slower sensory reweighting rather than to a maintained up-weighting of this sensory channel (Jeka et al. 2010). Hence, whether older adults are similarly affected by sensory manipulations when with eyes open and closed is yet to be explored.

Limitations. This study had some limitations. Firstly, the TENS device used did not allow to fully manipulate stimulation parameters, so as to create similar frequency content signals as in GVS and VMS. Secondly, the VMS signal was built to instantaneously reach 100 Hz, to exceed proprioceptor thresholds; this differs from the sinusoidal GVS or ramped (up and down) TENS stimulations signals. However, we did not aim to compare the effects of the different sensory manipulations and quantitative comparisons among the somatosensory, proprioceptive, and vestibular manipulations cannot be made, since comparable scaling of the stimulus intensities of the different sensory manipulation modalities was not possible. Between subjects variability was not considered; however, our sample consisted of healthy young subjects without impairments of the sensory systems or balance control system.

Practical implications. Although the use of visual feedback on balance performance has previously been used to assess balance (Cofre Lizama et al. 2013, 2014; Dault et al. 2003), its interaction with disturbances of sensory systems as a model for sensory impairment had not yet been studied. Since up-weighting of visual information might occur when explicit visual feedback is provided, diagnostic tests may overlook impairments of other sensory systems contributing to balance control. However, our results showed only limited interactions between explicit visual feedback on COM movements and sensory manipulations of the somatosensory, vestibular, and proprioceptive systems. The results of this investigation also show that ML sway was significantly increased for all manipulation modalities at their respective frequency content compared with control conditions even when explicit feedback was provided. Although effects of sensory manipulations will differ from the physiological changes in acuity of the senses with aging or due to pathology, the present results suggest that the use of feedback (up-weighting of visual inputs) in balance assessment will not mask sensory deficits.

Conclusion. Electrical stimulation of the foot soles and the vestibular system, alternating from left to right, as well as alternating vibratory stimulation of the muscle spindles in the hip abductor muscles, led to increased sway at the frequencies of the input signals. Absence of normal visual information had no effect on ML CoM sway, while explicit feedback on CoM reduced ML sway and reduced but did not efface the effects of manipulations of the somatosensory, vestibular, and proprioceptive systems. This investigation supports the potential of using explicit feedback on postural sway in assessing and training balance.

GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: L.E.C.L., M.P., N.P.R., S.M.P.V., and J.H.v.D. conception and design of research; L.E.C.L. performed experiments; L.E.C.L. and J.H.v.D. analyzed data; L.E.C.L., M.P., and J.H.v.D. interpreted results of experiments; L.E.C.L. prepared figures; L.E.C.L. and J.H.v.D. drafted manuscript; L.E.C.L., M.P., N.P.R., S.M.P.V., and J.H.v.D. edited and revised manuscript; L.E.C.L., M.P., N.P.R., S.M.P.V., and J.H.v.D. approved final version of manuscript.

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