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A wearable vibrotactile biofeedback system improves balance control of healthy young adults following perturbations from quiet stance

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Abstract:

Maintaining postural equilibrium requires fast reactions and constant adjustments of the center of mass (CoM) position to prevent falls, especially when there is a sudden perturbation of the support surface. During this study, a newly developed wearable feedback system provided immediate vibrotactile clues to users based on plantar force measurement, in an attempt to reduce reaction time and CoM displacement in response to a perturbation of the floor. Ten healthy young adults participated in this study. They stood on a support surface, which suddenly moved in one of four horizontal directions (forward, backward, left and right), with the biofeedback system turned on or off. The testing sequence of the four perturbation directions and the two system conditions (turned on or off) was randomized. The resulting reaction time and CoM displacement were analyzed. Results showed that the vibrotactile feedback system significantly improved balance control during translational perturbations. The positive results of this preliminary study highlight the potential of a plantar force measurement based biofeedback system in improving balance under perturbations of the support surface. Future system optimizations could facilitate its application in fall prevention in real life conditions, such as standing in buses or trains that suddenly decelerate or accelerate.

Keywords: wearable device; vibrotactile biofeedback system; balance; perturbation; center of mass displacement; reaction time

Highlights

A new wearable plantar-force based vibrotactile biofeedback system was introduced.

The system provided feedback regarding changes in forces at the fore- and rearfoot.

It improved initial reactions to translational perturbations.

Further optimizations are needed to facilitate fall prevention in real-life conditions.

1 Introduction

Falling can cause serious physical and psychological injuries, and can be fatal (Wood, et al., 2011). Globally around 400,000 people die because of falling each year (World Health Organization Ageing Life Course Unit, 2008). Sufficient balance control needs to be maintained during standing and walking on both static and moving support surfaces (Horak, 2006; Schoneburg, et al., 2013). Balance perturbation, which can be generated by support surface translation and sudden push/pull of the body (Mansfield, et al., 2015), poses great challenges to balance control (Sturnieks, et al., 2013). Trajectory of the body's center of mass (CoM) provides important information regarding the control of balance (Lafond, et al., 2004). Large displacement of CoM and slow reaction time in response to a floor translation perturbation have been suggested to be linked to higher risk of fallings (Owings, et al., 2001).

Following perturbation of the floor, three stages happened: 1) initial body tilt towards the opposite side of translation, 2) process of returning to postural equilibrium (recovery period, voluntary postural adjustment), and 3) reaching a new equilibrium position (Maki & McIlroy, 2007). Our central nervous system interprets the signals received from somatosensory, visual, and vestibular systems to detect changes in postural equilibrium during sudden perturbations (Maki & McIlroy, 2007). It then gives a postural response by transmitting signals to the muscles (Park, et al., 2004). During quiet standing, a sudden perturbation of the floor can provoke an ankle strategy (activation of plantarflexors, dorsiflexors, invertors and evertors of the foot) and a hip strategy (activation of hip flexors, extensors, abductors and adductors) to control body movements (Jones, et al., 2008), and these induce changes in force distributions under the feet (Yang & Pai, 2007). Tactile sensory input from the plantar foot is one crucial element for balance (Oliveira, et al., 2011), as it provides information for necessary adjustments of body posture and motion for maintaining balance (Eils, et al., 2004). Plantar sensation could be reduced by soft foot-supporting materials (Perry, et al., 2000), aging (Bretan, et al., 2010) and neuropathy (Jaiswal, et al., 2013). Providing additional feedback regarding changes in plantar force distribution could possibly be useful to improve balance following perturbations.

Some biofeedback systems have been developed, but there were limited indications suggesting these systems improved balance in response to perturbations. A biofeedback system developed by Sienko *et al.* (2012) provided subjects with instant vibrotactile clues when the measured degree of trunk inclination, which was provoked by a perturbation of the floor, exceeded certain thresholds. They reported reduction of recovery time but increase of body tilt after providing the clues (Sienko, et al., 2012). Rocchi *et al.* (2008) delivered auditory biofeedback to subjects standing on an unstable floor when the sensed trunk acceleration exceeded specific ranges. They found the changes of postural sway in both forward-backward and mediolateral directions were inconsistent among subjects (Rocchi, et al., 2008). Determining the appropriate thresholds of provoking biofeedback has been difficult. In addition, these studies used gyroscopes/inertia motion sensors that were attached to the trunk to detect body motion.

These tended to add weight and bulkiness to the entire trunk-mounted devices. Delivering biofeedback based on the plantar force measurement could be a good alternative option. This can augment plantar sensation which is important for balance control (Oliveira, et al., 2011), and potentially makes the monitoring of floor perturbations more sensitive as it directly measures the forces acting on plantar surfaces of feet. Thin-film plantar force sensors that are embedded into the shoes can also potentially reduce the size and mass of the device that is mounted to the trunk (C. Z.-H. Ma, et al., 2015; C. Z.-H. Ma, et al., 2016). So far, such kind of biofeedback systems with plantar force sensors were only configured for the use in static floor conditions (C. Z.-H. Ma, et al., 2015; C. Z.-H. Ma, et al., 2016; C. Z. Ma, et al., 2014).

This preliminary study attempted to reduce the CoM displacement and reaction time in response to the perturbation floor by developing and investigating a new wearable vibrotactile biofeedback system integrated with plantar force measurement. Four directions of translational perturbations were studied, including forward, backward, to the left and right sides, with the biofeedback system turned on and off. If the system is proven effective in improving balance control in a simple perturbation floor condition, future studies can look into the possibilities of its application in fall prevention in real life conditions, such as standing in buses or trains that suddenly decelerate or accelerate.

2 Methods

2.1 Vibrotactile biofeedback system integrated with plantar force measurement

The system comprised a plantar force acquisition and analysis unit (secured at the distal leg) as well as a vibration unit. The plantar force acquisition and analysis unit consisted of four thin-film force sensors (A301, Tekscan Co., Ltd, USA), a microprocessor (ATMEGA328P, Atmel Co., Ltd, USA), a rechargeable lithium ion battery (FLB-16340-880-PTD, UltraFire Co., Ltd, China) and a wireless transmitter module (HC-05, HC information Tech. Co., Ltd, China). The vibration unit consisted of four vibrators (XY-B1027-DX, Xiongying electronics Co., Ltd, China), a rechargeable lithium ion battery (FLB-16340-880-PTD, UltraFire Co., Ltd, China) and a wireless receiver module (HC-05, HC information Tech. Co., Ltd, China). The vibration frequency of the vibrators was 220Hz with a full strength of 1G that was greatly identifiable by human (Kyung, et al., 2005). The microcontroller converted the analog force data received from force sensors into digital data, analysed the measured plantar force data, and then sent a wireless control signal to the vibration unit if the measured forces exceeded certain thresholds. The sampling rate of the force sensors and signal transmission time was 10Hz and 0.67ms, respectively.

The four force sensors were adhered by adhesive tapes to a pair of 2mm-thick ethylene-vinyl acetate flat insoles at the positions of the first metatarsal heads and the centers of heels of both feet. The force values obtained from the four sensors were used to detect the anteroposterior, left and right body sways (Table 1). The vibrators were located at the sternum, the back, left and right arms, which corresponded to the anterior, posterior, left and right body sways, respectively. Each vibrator was activated instantly, only when the measured plantar force exceeded the pre-set force threshold. Identification of the thresholds is detailed in the section of experimental procedure.

2.2 Perturbation floor

The perturbation floor was made of a wood board (50cm×50cm), covered by a 12mm-thick soft Polyvinyl chloride (PVC) foam (ON1117, density 45kg/m^3, stiffness 7292N/m, AORTHA, Co., Ltd, Hong Kong). The foam resembled shoes with soft soles, which could reduce subject’s sensation over the floor reaction force (Perry, et al., 2000).

Translational movements of the wood board were brought by an actuator (MAR40×500-S, SHHAGO, Co., Ltd, China), which elongated at a constant velocity of 50mm/s. The velocity of 50mm/s was reached from a static condition in 0.05 seconds.

2.3 Subjects

A total of ten healthy young adults (5 males & 5 females, aged 21.2±1.0 years, height 166.9±7.4cm, weight 55.3±8.0kg), without medical conditions affecting balance or foot deformities, participated in the study. They were recruited from the authors' university. The foot condition was checked and the locations of force sensors were determined by a certified orthotist. All subjects signed written-informed consents before participating in the study. Ethical approval was granted from the Human Subjects Ethics Sub-committee of the authors' university (HSEARS20140211002).

2.4 Experimental procedure

The vibration threshold of the biofeedback system was first determined for each subject. This was done by 1) measuring forces under the feet using the system during static standing, with eyes opened, looking forward, feet together, and hands alongside the bodies for 30 seconds, and repeating the measurements three times; 2) averaging the plantar forces measured over the measurement period in the three trials for each sensor; and 3) adding the averaged force values of the two sensors that corresponded to each of the body tilting directions (see Table 1), and then multiplying by 120% to determine the threshold values. The vibrators were set to activate when the added instantaneous force values of two corresponding force sensors exceeded the pre-determined threshold. Our previous pilot studies had found that a multiplier of 120% was effective in reducing body sway. The threshold force values were acquired for each subject due to different plantar pressure distribution patterns among people (Machado, et al., 2016).

Subjects were then given a 10-minute practicing period to get familiar with the biofeedback system (Boonsinsukh, et al., 2011). They stood on the perturbation floor with feet together, hands alongside the bodies, eyes opened and looking forward. The floor moved in each of the four possible directions (forward, backward, left, and right side), with and without the biofeedback system turned-on. When the biofeedback system was used, subjects were instructed that the vibration of a vibrator indicated excessive body sway of a particular direction that required self-correction.

During the testing stage, subjects stood on the perturbation floor with the same posture as in the practice section. Each subject was tested with 40 successful trials (4 directions of perturbation × 2 conditions of the system (turned- on and off) × 5 successful trials for each direction and condition). The trial order was randomized. A trial was considered to be unsuccessful if the subjects stepped out of base of foot support in response to the perturbation (Hsu, et al., 2013). At each condition, the platform moved for a duration of 10 seconds without prior notice to the subjects. There was a helper standing next to the subjects for protection if necessary. The 40 trials lasted for less than 10 minutes.

2.5 Outcome measures

An eight-camera 3D motion analysis system (ViconNexus 1.7.0, Oxford Metrics, UK) was used to track the CoM movements. The position of CoM relative to the ground was determined by calculating the centroid of three reflective markers attached to the left and right anterior superior iliac spines, and the mid-point of left and right posterior superior iliac spines (Eames, et al., 1999). The maximum displacements of CoM (S_{max1}) opposite to the direction of perturbation, time to reach S_{max1} since the onset of perturbation (T_{peak}), displacements of CoM when reaching a new equilibrium position (S_{max2}), and duration between S_{max1} and S_{max2} (T_{rec}) were calculated (Figure 1). S_{max2} was identified at a point in the displacement-time curve at which the velocity of the COM movement approached the velocity of the perturbation floor and became steady thereafter. Due to continued movement of the perturbation floor, the CoM relative to the ground continued to move at a speed of 50mm/s after reaching $S_{max2.}$

Statistical analysis was conducted using the Statistical Package for Social Science (SPSS, version 22.0, IBM Corporation, Armonk, NY, USA) to analyse the effects of the two factors (system and perturbation direction) on each CoM parameter. There were two levels in system factor (turned on and off) and four levels in perturbation direction factor (forward, backward, left and right). Two-way repeated measures ANOVA were performed to examine the main and interaction effects of the two factors on S_{max1}, S_{max2}, T_{peak} and T_{rec}. If significant interaction effect was found, the simple effect of system (turned-on and turned-off) at each four directions of perturbations, and the simple effect of perturbation direction (forward, backward, left and right) at each condition of system would be further analysed. If significant interaction effect was not found but significant main effect of either system or perturbation direction was found, post hoc pairwise comparisons would be conducted to further understand where the significant differences among the levels of the factor laid, while collapsing over levels of the other factor. The level of significance was set as 0.05.

3 Results

Figure 1 shows typical CoM displacement-time patterns in each testing condition. As the perturbation floor moved, the CoM shifted to the opposite direction of the perturbation and reached S_{max1}. The CoM then moved towards the direction of floor movement, reaching a new equilibrium position S_{max2}. None of the subjects stepped out of base of foot support in response to the perturbation.

No interaction effects between system and perturbation direction was found in each of the four CoM parameters. Significant main effect of system was found in S_{max1} (p=0.010) and T_{peak} (p=0.015), with the S_{max1} and T_{peak} significantly reduced upon receiving the biofeedback cues. Specifically, the reductions of S_{max1} upon using the system in forward, backward, left and right perturbation were 12.6%, 11.8%, 12.4%, and 12.5%, respectively. Large average reductions of S_{max2} upon using the system were noted in forward, backward, left and right perturbation with 43.0%, 29.9%, 13.0%, and 27.5% drops, respectively, although significant differences were not reached.

Significant main effect of perturbation direction was found in T_{peak} ($p<0.001$) and T_{rec} (p=0.003). Post hoc pairwise comparisons further found that the T_{peak} during backward perturbation was significantly longer than that of the forward (p=0.036), left ($p<0.001$) and right (p=0.002) perturbation, and the T_{rec} during left perturbation was significantly shorter than that of the forward (p=0.021) and backward (p=0.025) perturbation.

4 Discussion

This study developed a new wearable feedback system which provided immediate vibrotactile clues to users based on plantar force measurement. Results suggested that the vibrotactile feedback system significantly improved balance control during translational perturbations. Its positive findings show its great potential in future fall prevention in real life conditions, such as standing on a bus or a train that suddenly decelerate or accelerate.

When a sudden surface perturbation is provided, the human body naturally tilts towards the opposite side of translation to a maximum displacement of S_{max1} due to inertia (Pai, et al., 2000; Santos, et al., 2010; Scholz, et al., 2007). The body then senses the movement and starts making a correction at T_{peak} (Pai, et al., 2000; Santos, et al., 2010; Scholz, et al., 2007), reversing to tilt towards the same direction of perturbation and reaches a new equilibrium position (S_{max2}) after T_{rec} (Pai, et al., 2000; Santos, et al., 2010). Thereafter, the body keeps the new postural equilibrium with little further CoM displacement (Santos, et al., 2010; Scholz, et al., 2007).

Large S_{max1} and T_{peak} in response to a floor perturbation have been suggested to be linked to poorer balance recovery and higher risk of fallings (Owings, et al., 2001). This study found statistically significant reductions of both S_{max1} and T_{peak} upon using the biofeedback system during surface perturbations. One possible explanation was that the vibration clues enabled users to sense the perturbation earlier, reducing the reaction time to the perturbation. This might then trigger the cognitive processing of postural movement and the upcoming anticipatory postural adjustments earlier, resulting in better control over the movement of CoM. This is supported by a previous study which found significantly larger maximum CoM displacement in healthy young subjects under an unpredictable surface perturbation condition, as compared to a predictable perturbation (Santos, et al., 2010).

The finding of this study was contradictory to one previous study which found no reduction of S_{max1} or T_{peak}, but reduction of T_{rec}, when using a vibrotactile biofeedback system with gyroscopes and accelerometers measuring directly the body tilt (Sienko, et al., 2012). The use of different sensing methods and thresholds for biofeedback could be the reason. The results from the current study and the study conducted by Sienko and her colleagues (2012) suggested that postural recovery time improved with inertial sensors on the trunk, while initial reaction improved with force sensors on the foot plantar surface in response to transitional perturbations. Future studies could explore for different posture recovery situations with different methods and placement of sensing apparatus. Attempts could be also made to combine both trunk-mounted inertial sensors and foot-placed force sensors and investigate if this could result in an even better balance improvement effects.

The T_{peak} in backward perturbation was found to be longer than the three other directions, and the T_{rec} in forward perturbation was longer than the left perturbation. This could be explained by a previous study which indicated that during fixed-support standing, a mediolateral perturbation induced activation of proximal leg muscles earlier than forward-backward translational perturbation (Torres-Oviedo & Ting, 2007). That could lead to earlier onset of peak leg and trunk torque integrals during the mediolateral perturbation (Jones, et al., 2008) which might help achieve postural equilibrium quicker.

No statistically significant reductions of S_{max2} and T_{rec} upon using the system were noted. Different threshold values were attempted in pilot studies, but they did not induce a consistent change in S_{max2} and T_{rec}. These results imply that while the biofeedback system could help the subjects to initiate the cognitive processing of postural movement and the upcoming anticipatory postural adjustments earlier significantly reducing S_{max1} and T_{peak}, it might not lead to consistent changes in re-establishing a state of postural equilibrium. Large standard deviations in S_{max2} and T_{rec} were found, suggesting that subjects used different approaches in attaining a new equilibrium position during floor perturbation. The relationships among S_{max2} and T_{rec} and risk of fall are not well known, which warrant further investigations. Future attempts could also adjust the sensor configurations and algorithm, and investigate the effects on S_{max2} and T_{rec}.

Comparing various physiological strategies that respond to a translational surface perturbation, a fixed-support strategy (no movements at the feet) predominately uses an ankle strategy in response to perturbation (Maki & McIlroy, 2006), while a change-in-support strategy where taking a step or reaching to an object for support is allowed predominately uses a hip strategy (Maki & McIlroy, 2006). This study instructed the subjects to use the fixed-support strategy only to standardize subjects' response to the translational surface perturbation. The fixed-support strategy is important in providing early defence against loss of balance (Maki & McIlroy, 1997). This strategy is also useful in a real-life situation of standing in a limited space, for example being crowded in a train. However, a change-in-support strategy has the potential of providing greater degree of stabilization (Maki & Mcilroy, 1999). The effects of the biofeedback system on reaction time and COM displacement could be different between the two strategies. Future studies could investigate the effects of biofeedback on balance control when subjects employ different strategies to recover balance and prevent falls in various real-life conditions. This could further facilitate the potential application of the system in fall prevention in daily life in the future.

All subjects in this study were healthy young adults, which limited the generalization of the findings of this study. Future studies should investigate the effects of plantar force measurement based biofeedback system on balance in other populations, such as the elderly and patients with balance disorders, who are more prone to fall. Future studies could also compare the differences between the use of plantar force and inertia sensors in changing balance control and investigate an optimum configuration of the sensing and feedback methods.

The measured CoM displacement was relative to the ground in this study. This truly reflected the CoM movement caused by both the perturbation floor and the regulation of body posture. While comparisons among different conditions were allowed as the perturbation floor moved at the same speed among repeated measurements of each subject, the data reported in this study might not be comparable to other studies which adopted different speeds of floor translation.

5 Conclusion

This preliminary study introduced a newly developed wearable vibrotactile biofeedback system, based on plantar force measurements, which was found to have significantly reduced the reaction time and maximum CoM displacement in translational support surface perturbations. The positive results implied better reaction and improved balance control in such perturbations. Thin-film plantar-force sensors offer an advantage that they can be embedded into the shoes, removing the need of mounting any sensors to the trunk. Further optimization of the system design and capability is suggested, facilitating its application in fall prevention in real life conditions, such as standing in buses or trains that suddenly decelerate or accelerate.

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8 Abbreviations

CoM: center of mass;

S_{max1}: maximum center of mass displacement opposite to the movement of floor;

S_{max2}: center of mass displacement toward the movement of floor when reaching a new equilibrium position;

T_{peak}: time to reach maximum center of mass displacement opposite the movement of floor (S_{max1});

T_{rec}: duration between S_{max1} and S_{max2} for center of mass to reach steady without more displacement.

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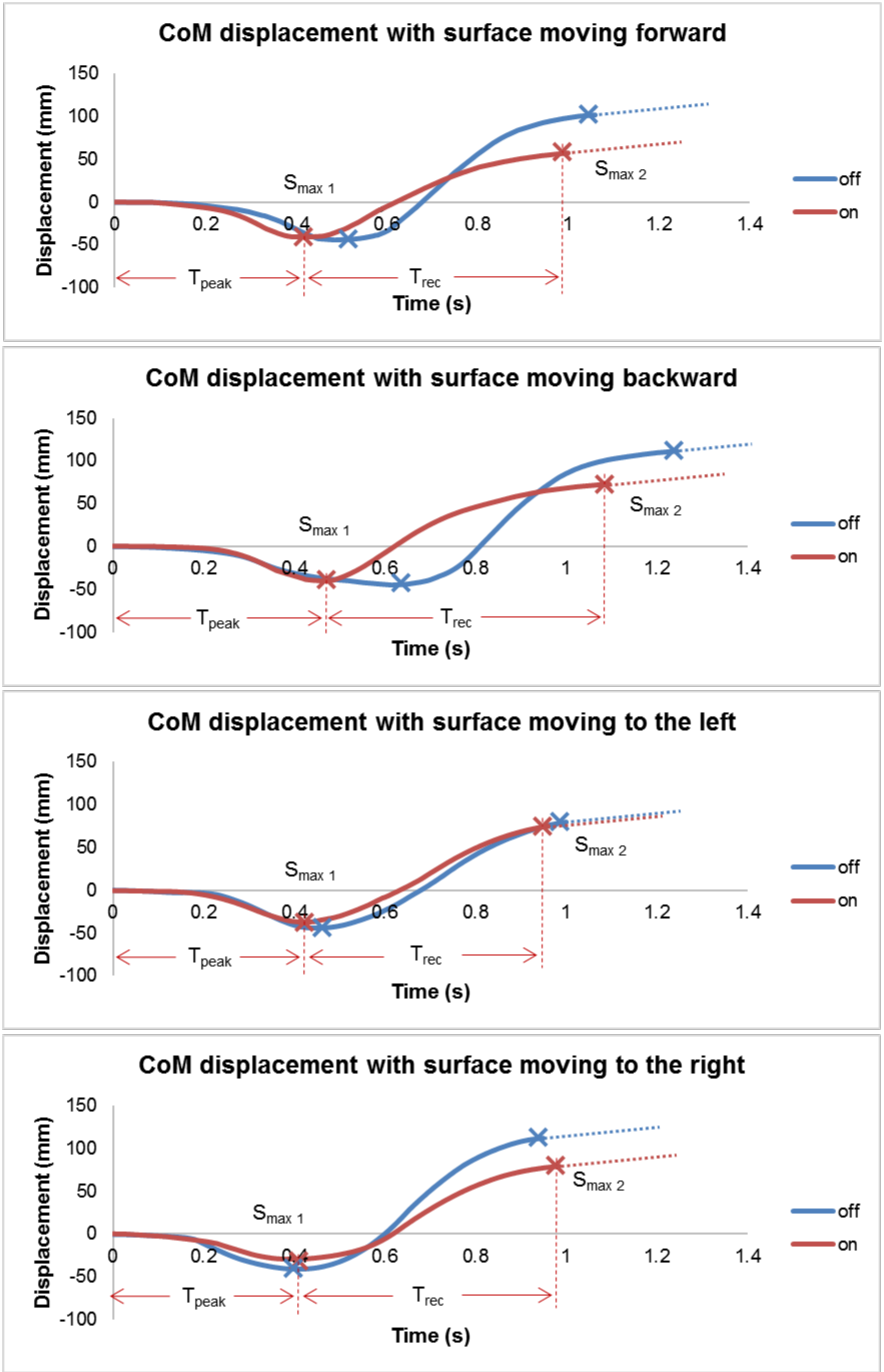

Figure 1. Example of CoM displacements in 8 experimental conditions in one subject.

Table 1. Location of the corresponding force sensors and vibrators for body tilt in forward, backward, left and right directions.

Direction of body tilt	Locations of a pair of force sensors used to detect one of the body tilting directions	Location of the corresponding vibrator
Forward	Left foot's metatarsal head (S0) & Right foot's metatarsal head (S1)	Sternum (V0)
Backward	Left foot's center of heel (S2) & Right foot's center of heel (S3)	Back (V2)
Left	Left foot's metatarsal head (S0) & Left foot's center of heel (S2)	Left arm (V3)
Right	Right foot's metatarsal head (S1) & Right foot's center of heel (S3)	Right arm (V1)

Notes:

- A vibration threshold was determined by multiplying 120% to the summation of force values measured by the pair of sensors

-The corresponding vibrator vibrated only when the summation of instantaneous forces measured by the sensor pair exceeded the vibration threshold.

Table 2. Comparison of CoM parameters with and without biofeedback provided (n=10).

Perturbation Direction	Parameters	Mean ± SD	
		Biofeedback Turned-on	Biofeedback Turned-off
Forward	S_{max1} (mm) *	36.5±11.3	41.7±12.8
	S_{max2} (mm)	54.2±21.7	95.0±41.1
	T_{peak} (ms) *, #	442.0±95.7	522.0±90.3
	T_{rec} (ms) #	641.0±80.1	660.0±90.3
Backward	S_{max1} (mm) *	40.0±10.0	45.3±7.9
	S_{max2} (mm)	66.0±29.6	94.2±44.3
	T_{peak} (ms) *, #	571.0±101.4	608.0±86.9
	T_{rec} (ms) #	685.0±101.9	679.0±92.2
Left	S_{max1} (mm) *	36.5±11.7	41.7±12.8
	S_{max2} (mm)	85.5±30.6	98.3±39.3
	T_{peak} (ms) *, #	411.0±130.3	421.0±77.1
	T_{rec} (ms) #	514.0±130.0	538.0±119.8
Right	S_{max1} (mm) *	34.2±14.4	39.1±15.3
	S_{max2} (mm)	78.1±31.3	107.8±40.7
	T_{peak} (ms) *, #	412.0±110.1	405.0±114.0
	T_{rec} (ms) #	558.0±128.0	551.0±137.3

Notes:

*: Significant main effect of system found

#: Significant main effect of perturbation direction found