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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 analysed. 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.

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, Mancini, Horak, & Nutt, 2013). Balance perturbation, which can be generated by support surface translation and sudden push/pull of the body (Mansfield, Wong, Bryce, Knorr, & Patterson, 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, Duarte, & Prince, 2004). Large displacement of CoM and slow reaction time in response to a floor translation perturbation have been suggested to be linked to

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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higher risk of fallings (Owings, Pavol, & Grabiner, 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, Horak, & Kuo, 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, Henry, Raasch, Hitt, & Bunn, 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, McIlroy, & Maki, 2000), aging (Bretan, Pinheiro, & Corrente, 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, Balkwill, and Wall (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, Benocci, Farella, Benini, and Chiari (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 (Ma, Wan, Wong, Zheng, & Lee, 2015; Ma, Wong, Lam, Wan, & Lee, 2016). So far, such kind of biofeedback systems with plantar force sensors were only configured for the use in static floor conditions (Ma et al., 2015; Ma et al., 2016; Ma, Wan, Wong, Zheng, & Lee, 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 220 Hz with a full strength of 1G that was greatly identifiable by human (Kyung, Ahn, Kwon, & Srinivasan, 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 10 Hz and 0.67 ms, respectively.

The four force sensors were adhered by adhesive tapes to a pair of 2 mm-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 (50 cm × 50 cm), covered by a 12 mm-thick soft Polyvinyl chloride (PVC) foam (ON1117, density 45 kg/m^3, stiffness 7292 N/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