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Michael Pollind

Rahul Soangra

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Development and Validation of Wearable Inertial Sensor System for Postural Sway Analysis

Michael Pollind¹ and Rahul Soangra^{2&3*}

¹Schmid College of Science and Technology, Chapman University, Orange CA 92866

²Crean College of Health and Behavioral Sciences, Chapman University, Orange CA 92866

³Fowler School of Engineering, Chapman University, Orange CA 92866

*Corresponding Author:

Rahul Soangra, Ph.D.

Assistant Professor

Department of Physical Therapy, Crean College of Health and Behavioral Sciences

Department of Electrical Engineering and Computer Sciences, Fowler School of Engineering

Room 229, 9401 Jeronimo RD, Chapman University, Irvine CA 92618

Abstract

Postural sway analysis is an important tool in fall risk analysis. A traditional way to measure postural sway is through forceplates by mapping Center of Pressure (COP) excursions or tracking marker position using motion analysis camera system. However, these systems are expensive and lack portability to their usage in clinical environments. In this study, a wearable low-cost MEMS inertial sensor was developed and validated for its usage in postural sway assessment. This study had two important objectives 1) To develop and validate an Inertial Measurement Unit (IMU) for sway analysis 2) To assess the feasibility of IMU in detecting slight balance impairments due to reduced proprioception or induced subthreshold vibrations on the feet. Sway velocity, Root Mean Square (RMS), and sway path length could successfully differentiate postural changes due to varying proprioceptive and sub-threshold vibration conditions. Wearable sensors are easy-to-use, portable and accurate devices for postural sway assessment in clinics.

INTRODUCTION

Postural control requires integration of sensory inputs from visual, vestibular, and somatosensory systems to maintain the center of gravity (COG) within the base of support. Postural balance encompasses a complex range of skills based on the dynamic interaction between sensory inputs and motor processes. Depending on the individual, task, and environmental conditions, maintenance of static and dynamic postural balance involves the integration of these three systems that are automatic and dynamic in a process called sensory reweighting (Shumway-Cook & Woollacott, 2007). Therefore, the healthy sensory system is essential for successful postural control in static and dynamic conditions. Impairments of any sensory system can lead to deficits

in postural control, resulting in increased risk for falls. The diminished tactile sensation of the sole and diminished ankle proprioception is common among patients in the geriatric population and specifically with diabetic neuropathy. This sensory loss decreases the feedback received by the central nervous system to correct postural responses and becomes reliant on visual and vestibular information (Bagherzadeh Cham, Mohseni-Bandpei, Bahramizadeh, Kalbasi, & Biglarian, 2016). Thus, it is not uncommon for balance to be impaired due to decreased somatosensory conditions. If we can simply amplify the sensory input that an individual with diminished somatosensory input faces, then it is possible to restore balance and decrease fall risk. Stochastic resonance is one such phenomenon in which white noise is introduced to boost a subthreshold signal to cross a receptor's sensory threshold; therefore, improving the system's sensitivity to detect the subthreshold proprioceptive information (Nobusako et al., 2018). Stochastic resonance can be defined as adding a weak input signal of noise to an already weak signal resulting in a stronger resultant signal that can surpass the sensory threshold of a neuron's receptor (White, Babič, Trenado, Johannsen, & Goswami, 2019). This can allow useful information to pass to the central nervous system and allow for an appropriate response and balance restoration. However, introducing a strong input signal of noise can bypass the original signal and the CNS may have a different response. Therefore, it was important in this study to provide noise that was subthreshold to the participants.

Some research studies have supported the use of stochastic resonance to improve balance and postural control in the elderly (Zhou, Lipsitz, Habtemariam, & Manor, 2016) and the diabetic population. The clinical and biomechanical effects of subthreshold random noise on the plantar surface of the foot in diabetic patients and older people have been demonstrated in some studies (Aboutorabi, Arazpour, Bahramizadeh, Farahmand, & Fadayevatan, 2018; Bagherzadeh Cham et al., 2016). In other studies, the noise was applied through vibrating actuators or motors that were embedded in shoe insoles to improve balance (Lipsitz et al., 2015). Outcome measures included force plate measurements for postural sway, postural sway via motion analysis, and temporal and spatial gait parameters via motion analysis (Miranda et al., 2016; Stephen et al., 2012). All of these studies indicated that subthreshold noise improved balance control, tactile sensation (Dettmer, Pourmoghaddam, Lee, & Layne, 2016; Hochreiter, Jewell, Barber, & Browne, 1983), and vibration sensation (Bagherzadeh Cham et al., 2016). The benefits of stochastic resonance have also improved balance in other populations such as Cerebral Palsy (CP). It was found that the application of stochastic resonance to children with CP significantly decreased their postural sway (Zarkou, Lee, Prosser, Hwang, & Jeka, 2018). In a randomized controlled trial to health care professionals with the experimental group given 8-weeks of stochastic resonance whole-body vibration training and the control group with no intervention (Elfering et al., 2014), it was found that the mediolateral sway was significantly decreased in the experimental group but not in the control group, indicating that it may be beneficial in preventing balance-related injuries at work (Elfering et al., 2014), as medial-lateral sway amplitude is considered strong predictor of fall risk (Sun, Hsieh, & Sosnoff, 2018). The aim of this study was to develop and test the determinism of sway signals of a new wearable sensor device developed in our laboratory (Mini-Logger) to the gold standard camera-based motion capture system with specialized sway platform with 4 Degrees of Freedom (DOF). This study also investigated the sensitivity of the novel sensor on human postural sway at different visual, proprioceptive and vibratory conditions.

In this study, the position of tactor was chosen as the dorsal aspect of 1st metatarsal of the foot and the frequency settings for the subthreshold noise (220 and 260Hz). Hennig and Sterzing evaluated that the touch and vibration perception threshold values from 30 plantar and dorsal point areas of the foot in healthy men and women with the average age of 20 to 35 years (Hennig & Sterzing, 2009). Their work utilized Semmes Weinstein monofilaments and a vibrotactile neurothesiometer to determine touch and vibration detection thresholds and found the regions that had best touch sensitivities, or lowest tactile sensory thresholds, were at the medial longitudinal arch, plantar surface of 1st, 3rd, and 5th toes, and dorsal surfaces of 1st, 3rd, and 5th toes. Although no differences between genders were reported lowest thresholds were found on the plantar surface of the foot as well as on the dorsal surface of the great toe (Hennig & Sterzing, 2009). Wells et al. reported the effects of aging on plantar vibration sensation on both vibration frequency and location (Wells, Ward, Chua, & Inglis, 2003). They reported 3 regions of high sensitivity on the foot - the ball/medial arch, the lateral border, and the toes (Wells et al., 2003).

In this study, we placed tactors on the dorsal aspect of the distal 1st metatarsal. Dettmer et al. tested noise signals ranging from 1 Hz to about 500 Hz to include vibration frequencies that can be captured by multiple mechanoreceptors of the foot (Dettmer, Pourmoghaddam, Lee, & Layne, 2015). Since vibro-medical insole, vibration sensation improved balance when affixed at the big toe of both feet with a 256 Hz tuning fork but no significant effect found with 128 Hz tuning fork, we tested for frequencies at 220Hz and 260Hz (Bagherzadeh Cham, Mohseni-Bandpei, Bahramizadeh, Kalbasi, & Biglarian, 2018). Wells et al. applied vibration at 4 different frequencies - 25, 50, 250, and 400 Hz - to regions on the foot in young and elderly people. It was found that for both young and old people, the lowest detection threshold was determined at 250 Hz at the toes, ball/arch, and lateral border of the foot (Wells et al., 2003).

With a thorough review of the evidence regarding the application of stochastic resonance, we have found a lack of single randomized controlled studies that looked at the effect of stochastic resonance on balance to a task (i.e. standing) under various sensory conditions (i.e. eyes open/closed, stable/unstable surface). We have also found a lack of evidence on the appropriate noise frequencies that can be used. The purpose of this study is to determine the effects of stochastic resonance on healthy young adults during standing posture and under various sensory conditions. These conditions simulate the sensory deficits that are found among the older adults, patients with stroke, and patients with diabetic neuropathy. We hypothesized that stochastic resonance can increase subthreshold input signals when there is a sensory impairment and thus improve balance.

Methods

Experiment 1- Development of IMU: Currently, many of the sensors used to collect acceleration and gyroscopic data are expensive and cost upwards of 1000 USD. We designed an IMU named Mini-Logger to be a more affordable IMU for human postural sway analysis. It is a small wearable sensor that was designed to collect linear acceleration and gyroscopic moments at a variable frequency up to 100Hz; the data is saved onto a removable micro SD card.

Figure 1: Design and fabrication of IMU, named Mini-Logger

The Mini-Logger follows a similar construction to an Arduino Pro Mini - containing a microprocessor (ATmega-328-AU), power supply (3.3V), and 6 programmable pin headers. The data acquisition component is an ICM-20498, a 9 axis (3-axis gyroscope, 3-axis accelerometer, and 3-axis compass) motion tracking device. For the purposes of this sensor, only 6 axes are used. The ICM-20498 was chosen because of the compact size of the chip and a very low power requirement in comparison to other motion tracking devices. While the lower power consumption is an advantage for extending the battery life, it does create a challenge of connecting the chip to the rest of the board. The ICM-20498 has an operating voltage of 1.81 volts whereas the other components use 3.3 volts. In order to combat this problem, an I2C bridge (2004PCA9306DCUR) was added to convert the higher voltage of 3.3V to 1.8V, allowing the ICM-20498 to draw power directly from the board instead of an additional external power source. Before the data is stored onto the SD card, the signals from the ICM-20498 are passed to the microprocessor. The enclosure for the Mini-Logger was designed in Autodesk Fusion 360. A simple snap-fit design was used to secure the sensor inside the enclosure. All fabrication details are available at https://github.com/GaitRehabilitation/mini_data_capture.

Validation of IMU: The performance of IMU was tested against a gold-standard infra-red motion capture camera system for assessing sway. The sensor was mounted on a treadmill platform with 4 Degrees of Freedom (DOF) Figure 2a. The repetitive motion produced by the platform was an ideal setup for validation of sway measured by the two systems i) IMU and ii) Infra-red Marker. The platform could generate 10 degrees of pitch and 5 cm of translation. Two sinusoidal equations were used for pitch and translation as shown in equations 1 and 2 below.

$Pitch = percent_{magnitude} * 10 * \sin(percent_{frequency} * TIME)$	1
$Translation = percent_{magnitude} * 0.05 * \sin(percent_{frequency} * TIME)$	2

The Percent_{magnitude} and Percent_{frequency} ranged from 100%, 80%, 40% and 20% of the total range of motion. For example, pitch (maximum amplitude 10 degrees) had an amplitude of ± 10 , ± 8 , ± 4 , ± 2 degrees and translation of ± 5 , ± 4 , ± 2 , ± 1 cm of horizontal motion. The movement data was filtered using zero-lag low-pass Butterworth filter of 4th order and cut-off frequency as 8Hz.

Figure 2: (a) Platform with various degrees of freedom to generate sway (b) Various amplitude and frequency of sway generated (c) Sensor and Infra-red Marker (d) Sinusoidal waves showing amplitude and frequency generated

Nonlinear analysis such as Recurrent Quantification Analysis (RQA) was used to validate recurrence and determinism between signals from the infra-red marker and IMU, which were generated from a single movement source (platform here Figure 2a). The platform is a part of the Gait Research Analysis and Interactive Laboratory (GRAIL, Motek Medical, Netherland). RQA is used to quantify the duration and number of recurrences in the time series. The time delay and the number of dimensions to embed the signal were computed (Wallot & Mønster, 2018). Average Mutual Information (AMI) is used to find optimal delay for embedding. Independence is quantified by $((x(t), x(t + \tau)))$ where τ is a constant that shifts the signal by some factor from original $x(t)$ and $x(t+\tau)$ (Wallot & Mønster, 2018). This can be resolved by a nonlinear generalization of the auto-correlation function and is given by equation below(Wallot & Mønster, 2018)

$I(x(t), x(t, \tau)) = \sum_{i,j} (p_{i,j}(\tau) \log (\frac{p_{i,j}(\tau)}{p_i p_j}))$	3
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False Nearest Neighbors (FNN) is used to find the optimal lag of the signal(Wallot & Mønster, 2018). A state-space is reconstructed by embedding the original one-dimensional time series utilizing time delayed signals. This can be described by the original time series $X(t)$ and follows:

$y(t) = (x(t), x(t + \tau), \dots, x(t + (D - 1)\tau))$	4
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Where t and τ are integers that are indexed on the sample data (Wallot & Mønster, 2018). The embedding dimension (m) can be estimated by examining the distance between points in phase space. If the embedding distance between the two neighbors changes appreciably then the neighbors are considered false neighbors and are true neighbors otherwise(Wallot & Mønster, 2018). This is continued until the number of FNN drops to 0 or minimum(Wallot & Mønster, 2018).

Recurrent Quantitative Analysis (RQA) plots: The diagonal structure in the recurrence plots (RP) tends to suggest that the time series function has period to quasi-periodic recurrent structures(Marwan, Carmenromano, Thiel, & Kurths, 2007). This regularity in the structure suggests that the movement signal source repeated at a fixed interval(Marwan et al., 2007). However more quasi-period systems will have variations in the distance between diagonal segments(Marwan et al., 2007). The source for the signal was a fixed sinusoidal wave so this is expected when reviewing the recurrence plot data. Figure 3 shows how the recurrence plot can be constructed from accelerometer signals with known delay and dimensions.

Recurrence Rate (RR)

$RR_{\tau} = \sum_{i=1}^{N-\tau} (R_{i,i+1})$	5
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The distance between diagonal lines in RP space is referred to as the recurrence rate (RR). $P(l)$ is defined as the number of points sampled on the diagonal line segment(Marwan et al., 2007), or the histogram of the lengths l of the diagonal lines. The main diagonal for the RP plot is fixed across all the trials and is excluded when examining the RR. RR_{τ} is described by the equation above where $\tau=0$ is the main diagonal and $\tau>0$ is above the main diagonal and $\tau<0$ is the below the diagonal(Marwan et al., 2007). This measure directly relates to the likely hood that an event will occur again given some delay τ . This can be generalized as a higher-order autocorrelation function as it is dependent on τ (Marwan et al., 2007). Determinism (DET) is defined as the percentage of recurrence points which form the diagonal lines

$DET = \frac{\sum_{l=l_{min}}^N lP(l)}{\sum_{l=1}^N lP(l)}$	6
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Figure 3: Accelerometer signals from the platform sway were filtered for high-frequency noise and phase space reconstruction was performed for recurrence quantification

Experiment 2- Testing on Human Subjects: The goal of this experiment was to determine if the Mini-Logger has the ability to detect changes in postural sway depending on different proprioceptive, visual and vibration conditions. Participants were blinded to frequency settings and conditions that were randomized to reduce the possibility of ordering effects. Ten healthy subjects (5 males and 5 females, age: 27.3 ± 2.7 years, 68 ± 5.6 Kg, 183 ± 4 cm) were recruited to participate in this study which was approved by Chapman University IRB. Subjects provided informed consent as per Chapman University IRB and were evaluated on the ability to maintain balance with eyes open and with eyes closed, intact sensation of the foot, and intact proprioception of the ankle. Subjects were excluded if they presented with foot pain while barefoot or required orthotics.

Experimental Protocol: Static balance for each subject was assessed under a variety of conditions in randomized order, adjusting variables of visual input, proprioceptive input, and frequency, for a total of 12 conditions. For vision, participants were instructed to keep eyes open (EO) and focus on a target five meters ahead or to keep eyes closed (EC). Proprioceptive input was modified by adjusting surface conditions, having the participant stand directly on the solid vinyl surface or on STEPRIGHT® stability trainers (Figure 4a, 4b, 4c). Varying frequency input was provided with tactors placed on the dorsal surface of 1st MT on bilateral feet (0Hz, 220Hz, 260Hz). The amplitude of frequency stimulation was adjusted to subthreshold levels so that

subjects were unable to perceive vibration. Under each condition, subjects were instructed to stand on a force plate for a total of 60 seconds. Both motion capture systems infra-red marker and IMU device were placed on the back of each subject during trials. A physical therapy student was always present to adjust settings to appropriate conditions and to assist the participant. During the data collection, the students were asked to stand in place for one minute and had to undergo one of 12 conditions, shown in Table 1 below. Each condition was selected at random for each participant. The different conditions tested were as follows: eyes open, eyes closed, different tactor frequency (0Hz, 220Hz, 260Hz), even surface and uneven surface. For the vibration tactor trials, a tactor was attached to the first metatarsal (Figures 4c and 4d) and the frequency was changed in order to see if the balance of the student would change. For the trials without and with StepRight system were used to lower the points of contact of the foot(Figure 4b).

Table 1: Different conditions of postural standing

Condition #	Tactor Frequency	Eyes Open/Closed	Surface Condition
Condition 1	0HZ	EO	No StepRight
Condition 2	0 Hz	EO	StepRight
Condition 3	0 Hz	EC	No StepRight
Condition 4	0 Hz	EC	StepRight
Condition 5	220 Hz	EO	No StepRight
Condition 6	220 Hz	EO	StepRight
Condition 7	220 Hz	EC	No StepRight
Condition 8	220 Hz	EC	StepRight
Condition 9	260 Hz	EO	No StepRight
Condition 10	260 Hz	EO	StepRight
Condition 11	260 Hz	EC	No StepRight
Condition 12	260 Hz	EC	StepRight

Figure 4: (a) StepRight for reduced proprioceptive inputs (b) inflated StepRight (c) Tactors attached at first metatarsal when using StepRight and standing on forceplate (d) standing without StepRight on forceplate with tactors

Results:

Figure 5: (a) shows the sway path mapped by an infra-red marker (b) shows the sway path mapped by a triaxial inertial sensor

The sway path mapped by motion capture camera system and the wearable inertial sensor is mapped in Figures 5a and 5b. The motion capture camera system has a global center that is fixed at a point in the laboratory and all sway measured by markers are with respect to that origin. However, the Mini-Logger has its own reference origin and the origin moves with the sensor. Thus, all data acquired by the sensor is relative to its dynamic origin, which is swaying on the platform. Quantifying and comparison of sway from two different systems (camera system versus IMU) are only possible if properties of source signals could be compared. In this study, we explore the recurrence and determinism of the signals produced by the two systems. The recurrence rate and determinism from the resultant sway signal are shown in Table 2 below. We found that the recurrence rate is affected by noise in IMU and are found always less than that from the camera system. However, determinism is comparable in both of the systems (Figure 6). The RQA plots for different amplitudes and frequencies for the inertial sensor and marker data are shown in figure 7.

Table 2: Recurrence and determinism of resultant sway from marker and IMU data at different frequencies and amplitudes.

Amplitude	Frequency	Variable	Camera System	IMU
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20	20	Determinism	0.996	0.995
		Recurrence Rate	0.034	0.665
	40	Determinism	0.979	0.994
		Recurrence Rate	0.023	0.741
	80	Determinism	0.999	0.999
		Recurrence Rate	0.031	0.999
	100	Determinism	0.999	1
		Recurrence Rate	0.028	0.999
40	20	Determinism	0.996	0.998
		Recurrence Rate	0.017	0.922
	40	Determinism	0.999	1
		Recurrence Rate	0.018	0.999
	80	Determinism	0.998	1.000
		Recurrence Rate	0.014	0.999
	100	Determinism	0.999	0.999
		Recurrence Rate	0.013	0.999
80	20	Determinism	0.998	0.999
		Recurrence Rate	0.009	0.999
	40	Determinism	0.999	0.999
		Recurrence Rate	0.008	0.999
	80	Determinism	0.999	0.999
		Recurrence Rate	0.006	0.996
	100	Determinism	0.999	0.999
		Recurrence Rate	0.006	0.998
100	20	Determinism	0.999	1
		Recurrence Rate	0.006	0.999
	40	Determinism	0.999	0.999
		Recurrence Rate	0.006	0.999
	80	Determinism	0.999	0.999
		Recurrence Rate	0.004	0.984
	100	Determinism	0.998	0.999
		Recurrence Rate	0.004	0.990

Figure 6: Determinism in camera system and IMU system were found to have similar profiles when combination of four different frequencies and four different amplitudes of pitch and one-directional sway were tested.

Figure 7: a) RQA plots of inertial sensor sway signals b) RQA plots of marker sway signals

Data Analysis: Data was analyzed using multivariable analysis of variance (MANOVA) using JMP Pro software. The significance level was set at $p < 0.05$ for all analyses. We found RMS of signals when using StepRight (reduced proprioceptive condition) at 0Hz ($\bar{x} = 0.035$) was significantly higher ($p = 0.0155$) when compared to the condition when using StepRight at 220Hz ($\bar{x} = 0.026$) (Figure 8). However, no differences were observed at 260Hz.

Figure 8: RMS of sway decreased significantly at 220Hz

Figure 9: shows sway velocity differences with and without StepRight conditions

The sway velocity increased significantly ($p < 0.0001$) when using StepRight in the eyes-closed condition (Figure 9). Similarly, the sway path increased significantly ($p < 0.0001$) in the eyes-closed condition using StepRight (Figure 10).

Figure 10: Sway path increased significantly with StepRight usage.

Discussion

The primary objective of this study was to build a wearable system, validate it with gold-standard laboratory equipment and evaluate its relative sensitivity for sway measures to different proprioceptive and visual conditions. An IMU (Mini-Logger) was designed and fabricated (Figure 1) and was validated for sway analysis on a 4-DOF platform (Figure X). The movement was generated using two sinusoidal patterns generated in pitch and translation. In this study, healthy individuals were tested on a variety of proprioceptive, sub-threshold vibratory tactile inputs and visual inputs (EO versus EC) conditions. The IMU and camera system both sampled at the sampling frequency of 100 Hz. Since it is practically impossible to align the directions (axes) of global origin (for camera system) and sensitive directions of IMU, our analysis is based on resultant movement sensed by the two systems (Figure 5a and 5b).

The method of recurrence plots was utilized to visualize the behavior of trajectories in the m-dimensional phase space, which could represent the dynamics of the moving platform. The RQA provides measures based on diagonal structures (Webber & Zbilut, 1994). For example, two important movement-based variables i) recurrence rate and ii) determinism were computed. We found that percent recurrence and determinism in signals could be more informative for a common source of the signal (sinusoidal platform movements here). A signal is deterministic if there is no uncertainty with respect to its value at any instant of time. Recurrence plots can be generated which show for each moment in time, the times at which a phase space trajectory visits roughly

the same area in the phase space (Figure 3). We found that recurrence plots are sensitive to the change of signal properties in the course of time, and are affected by high-frequency noise. We performed RQA of the movement signals for 4 different frequencies and 4 different amplitude combinations of sway (Table 1). We found that the recurrence rate was highly dependent on noise and was affected by the noise in Mini-Logger, but determinism was found to be equivalent to both the systems (Table 2). This study validated the measured signals originated from a common source. To identify if wearable sensors are sensitive to varying proprioceptive, tactile inputs and visual inputs. A combination of 12 postural conditions was tested among 10 healthy subjects as shown in Table 1. This study investigates the effect of various frequencies of stochastic resonance on the postural sway of healthy young adults during quiet stance under conditions challenging their three sensory systems.

We found that fluctuations in human postural sway as evaluated using Root Mean Square (RMS) were affected due to the frequency of vibration. We found that postural sway, as represented by RMS, increased across all conditions when subjects were instructed to stand on the StepRight (a condition with decreased proprioceptive inputs), compromising somatosensory information from the ground. However, our results revealed that stochastic resonance during these somatosensory-compromised conditions improved postural sway compared to control groups without vibratory input (Figure 8). These results are in agreement with previous research examining the effects of stochastic resonance on postural sway (Bagherzadeh Cham et al., 2016; Cloutier et al., 2009; Galica et al., 2009; Hijmans, Geertzen, Zijlstra, Hof, & Postema, 2008; Khaodhiar et al., 2003; Priplata, Niemi, Harry, Lipsitz, & Collins, 2003; Priplata et al., 2006; Stephen et al., 2012; Wang & Yang, 2012; Wei et al., 2012). We found significant improvements in sway fluctuation measurements at the vibration frequency of 220Hz. Whereas no difference was observed between control trials and trials with a vibration frequency of 260Hz. These results suggest that there may be an ideal frequency at which stochastic resonance can be applied in order to promote good standing balance.

We also found higher postural sway velocity and path length for young healthy adults when standing on the StepRight with eyes closed. Whereas the use of the StepRight alone did not yield any significant changes in the postural control of healthy adults, the additional task of closing one's eyes was significantly challenging their balance during quiet stance, as demonstrated by a marked increase in postural sway velocity and path length. As discussed, postural control and balance depend on the integration of sensory inputs from our visual, vestibular, and somatosensory systems (Shumway-Cook & Woollacott, 2007). In the case of decreased access to somatosensory inputs provided by the StepRight, and the removal of visual input from eyes closed (EC) condition with limited sensory systems and modified weighting (or dependence) on vestibular and somatosensory inputs to maintain postural control. These changes in postural sway were sensitively identified by IMU. Wearable sensors are widely being used for investigating fall risk assessment and fall predictions (Frames et al., 2018; Lockhart, Frame, Soanra, & Lach, 2014). Wearable sensors will be helpful to clinicians to identify patients with high fall risk and guide interventions to prevent falls in acute-care settings. Currently, no tools exist to guide clinicians and health care professionals in assessing the risk of fall injury or

unanticipated falls. In such scenarios, wearable sensors could be helpful to identify patients with a high risk of falls in clinical environments.

Conclusion

This work contributes to the development of cheap wearable sensor, capable of measuring postural sway and assess fall risk. Our current findings show that IMU's can be readily designed and developed and used in measuring postural control. Wearable inertial sensors offer the opportunity of sensitive and objective balance assessments with high clinical feasibility due to small size, non-invasiveness, and portability. The work also contributes to developing novel methods for validation of sway sensed by two different systems. In conclusion, the development of cheap wearable systems can be utilized to prevent falls, fall-related injuries, and thereby improve the quality of life of older adults and reduce medical costs related to falls.

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