The Effects of Coding Schemes on Vibrotactile Biofeedback for Dynamic Balance Training in Parkinson's Disease and Healthy Elderly Individuals

Beom-Chan Lee, *Member, IEEE*, Alberto Fung, and Timothy A. Thrasher

***Abstract*— Coding scheme for earlier versions of vibrotactile biofeedback systems for balance-related applications was primarily binary in nature, either on or off at a given threshold (range of postural tilt), making it unable to convey information about error magnitude. The purpose of this paper was to explore the effects of two coding schemes (binary versus continuous) for vibrotactile biofeedback during dynamic weight-shifting exercises that are common physical therapists' recommended balance exercises used in clinical settings. Nine individuals with idiopathic Parkinson's disease and nine healthy elderly individuals participated in this paper. All participants performed dynamic weight-shifting exercises assisted with either the binary or continuous vibrotactile biofeedback delivered using with vibrating actuators (tactors) in either the anterior–posterior or medial–lateral direction. Participants' limits of stability at pre and post exercises were compared to evaluate the effects of the exercises on their range of motion. The continuous coding scheme produced significantly better performance than the binary scheme when both groups were performing dynamic weight-shifting balance exercises with assistive vibrotactile biofeedback. The results have implications in terms of maximizing the effects of error-driven motor learning and increasing performance on balance rehabilitation training combined with vibrotactile biofeedback.**

***Index Terms*— Vibrotactile biofeedback, continuous coding scheme, weight-shifting balance exercise, Parkinson's disease, elderly.**

I. Introduction

CLINICAL studies have shown that balance rehabilitation training is effective in promoting movement coordination and unsteadiness of posture in different populations (e.g., older adults [1], individuals with vestibular dysfunction [2], and individuals with Parkinson's disease (PD) [3]). However, cost, limited availability of physical therapists, limited access to clinical facilities, and poor motivation often prohibit participation in balance rehabilitation regimens [4]–[6]. User compliance also tends to decrease in the absence of real-time therapeutic feedback [7]–[9]. Consequently, there is growing interest in assistive device design and development utilizing biofeedback technology.

Biofeedback technology typically augments compromised sensory information with reliable senses (e.g., visual, auditory, and tactile cues) and facilitates retraining of sensorimotor functions during rehabilitation. Rehabilitation training combined with biofeedback technologies modifies existing and develops new pathways within the central nervous system (CNS) [10], which is known as neuroplasticity. Biological and clinical studies have shown that biofeedback-assisted rehabilitation training also promotes neuroplasticity in the basal ganglia [11]–[13]. Furthermore, the concurrent use of biofeedback during motor tasks can promote task learning, increase retention, and motivate repetitive exercising [14]–[20], thereby enhancing sensorimotor function recovery.

Multiple studies have noted the beneficial effects of balance rehabilitation training combined with visual, auditory, and/or vibrotactile biofeedback on different populations (see [17], [21] for review). Compared to visual and auditory biofeedback displays, vibrotactile biofeedback presents the most direct modality on sensorimotor adaptation [22]. Vibrotactile biofeedback occurs unobtrusively, under clothing, and does not interfere with important visual and auditory exteroceptive information [23]. In 2001, Wall *et al.* [24] pioneered a wearable vibrotactile biofeedback system to improve postural control in individuals with vestibular deficits. A typical vibrotactile biofeedback system for balance-related applications has an Inertial Measurement Unit (IMU) and vibrating actuators (tactors) [25], [26]. The IMU incorporating a tri-axial accelerometer, gyroscope, and magnetometer placed on the lower back corresponding to the body's center of mass (COM) measures body sway. The tactor array commonly located around the torso provides cutaneous stimulation to indicate

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B.-C. Lee is with the Department of Health and Human Performance, University of Houston, Houston, TX 77204 USA, and also with the Michael E. DeBakey Veterans Affairs Medical Center, Houston, TX 77030 USA (e-mail: blee24@central.uh.edu).

A. Fung is the Department of Health and Human Performance, University of Houston, Houston, TX 77204 USA (e-mail: afung@uh.edu).

T. A. Thrasher is with the Department of Health and Human Performance, University of Houston, Houston, TX 77204 USA (e-mail: athrashe@central.uh.edu).

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postural deviations from upright posture. More specifically, when the measured body sway exceeds a pre-defined threshold (i.e., range of postural tilt), the tactors "tell" the user to take corrective action.

To date, most vibrotactile biofeedback systems are designed to send "alarm" signals with a binary coding scheme (either on or off) about postural deviations [25]–[32]. It is speculated that the main reason for choosing a simple coding scheme (i.e., binary coding scheme) is attributed to the fact that the primary purpose of providing vibrotactile biofeedback is to inform the user about postural deviations associated with a pre-defined threshold during static standing tasks (e.g., normal (feet hip-width apart), Romberg (feet side-by-side), semi-tandem Romberg (feet staggered), and tandem Romberg (heel-to-toe) balance exercises)) [25], [28]–[30]. While knowledge of error magnitude both reinforces the preferred direction of motion and helps the user dynamically determine body position while exercising [33], the binary coding scheme is unable to convey information about error magnitudes of the body movement. One potential way to display error magnitudes uses a multiple-row by multiple-column array configuration of tactors to encode information of different levels of body position, which is known as a position-based magnitude coding scheme [26], [27]. However, this method does not provide error magnitudes between rows and columns and increases the cost and complexity of the instrumentation. An alternative option to the position-based magnitude coding is an intensity-based magnitude coding scheme that has been typically used for motion guidance applications in which the intensity-based magnitude coding scheme has reduced motion error between the desired and actual limb trajectories during dynamic tacking tasks (e.g., [34]).

Recognizing the need to present the error magnitude for vibrotactile biofeedback during balance-related exercises, we 1) describe the system design of a continuous coding scheme that encodes real-time error magnitude for vibrotactile biofeedback, and 2) quantitatively assess the effects of two coding schemes (binary and continuous) on exercise performance during dynamic weight-shifting exercises (physical therapists' recommended dynamic balance exercises in clinical and/or home settings) in PD and healthy elderly individuals. Our eventual goal is to improve our smartphone-based balance rehabilitation system [35] that can be used in the home or a limited environment (e.g., rural and underdeveloped area with limited access to balance therapy) to provide end-users with therapist-assigned balance exercises.

II. Methods

A. Vibrotactile Biofeedback System for Dynamic Weight-Shifting Exercises

The vibrotactile biofeedback system consists of a commercial six degree-of-freedom IMU (Xsens Technologies, NL), four C2 tactors (Engineering Acoustics Inc., Casselberry, FL, USA), and custom software. The IMU measures angular displacements and velocities in the anterior-posterior (A/P) and medial-lateral (M/L) directions. The C2 tactor, a linear actuator with a cylindrical moving contactor, was used to provide vibrotactile biofeedback. Manufacturer specifications indicates that vibration amplitude and frequency of the C2 tactor can be separately controlled by sinusoidal waveforms (Engineering Acoustics Inc., Casselberry, FL, USA). The vibration frequency of C2 tactors was selected as 250 Hz to fit within the one-to-one frequency response of fast-adapting cutaneous receptors [36], [37]. The maximum peak-to-peak amplitude of C2 tactors was 200 μm [38]. The IMU and tactors were attached with Velcro to an elastic waist belt worn around the torso. The IMU was placed on the lower back corresponding to the body's approximate COM, at the level of the L5/S1 vertebra. Four tactors were placed on the skin over the front, back, and right and left sides of the torso approximately at the level of the L4/L5 vertebra.

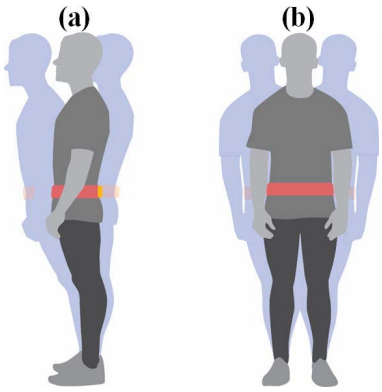

Fig. 1. Illustration of the dynamic weight-shifting balance exercises in the A/P (a) and M/L (b) direction.

Custom software, implemented using Microsoft Visual C++, sampled A/P and M/L angular displacements and velocities of the IMU at a rate of 100 Hz and provided vibrotactile biofeedback for the dynamic weight-shifting balance exercises. The weight-shifting exercises are commonly recommended by physical therapists, and they involve swaying the body smoothly and rhythmically in the A/P and M/L direction [39], [40] as illustrated in Fig. 1. The custom software generated the target motion based on 90% of the participants' measured limits of stability (LOS) in each of the four movement directions (i.e., A/P and M/L direction), as shown in Fig. 2 (a). Movement speed was set to 1 deg/s, which is the preferred speed for the dynamic weight-shifting balance exercises in a clinical setting [39], [40]. A control scheme for vibrotactile biofeedback is described in detail in our prior publications [31], [32]. Briefly, a proportional plus derivative control scheme based on differences in both body sway angle and angular velocity between the target and participant's motions was used to determine the motion error. For the binary coding scheme, the custom software activated the tactors with the maximum peak-to-peak amplitude when the absolute motion error exceeded 1.0 deg [31], [32], as shown in Fig. 2 (b). All tactors were deactivated when the absolute motion error dropped below 1.0 deg. For the continuous coding scheme, the intensity of tactors was continuously modulated as a function of the magnitude of the absolute motion error between 0 deg and 1 deg, as shown in Fig. 2 (b). Thus, the

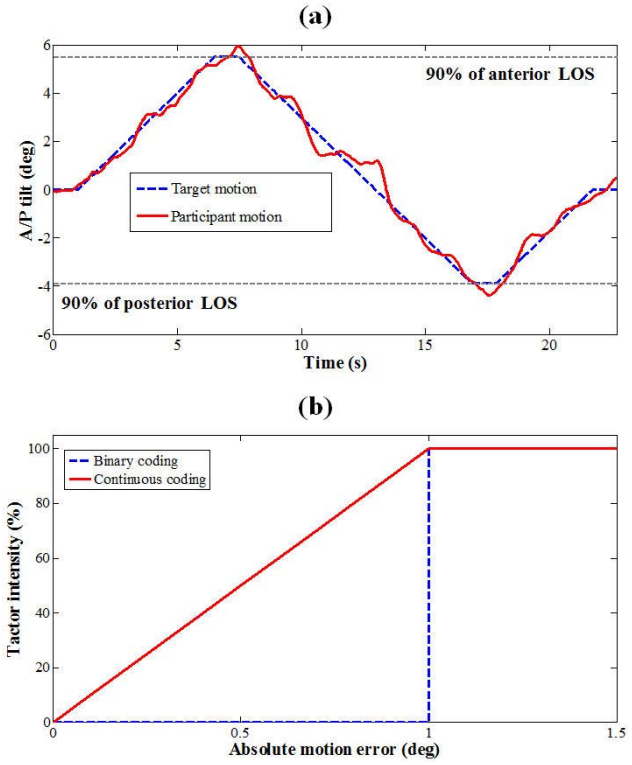

Fig. 2. (a) Representative data from one participant in the PD group during the A/P dynamic weight-shifting exercise. Dashed blue and solid red lines represent the target motion and participant's motion, respectively. Dashed grey lines represent the participant's 90% of LOS in both the anterior and posterior directions. (b) A mapping rule of the absolute motion error between the target motion and participant's motion to the intensity of the tactor. Dashed blue and solid red lines represent the binary coding scheme and continuous coding scheme, respectively.

continuous coding scheme enables the user to encode error magnitude information within a 1 deg motion error in real-time.

B. Participants

Nine individuals with PD (67.1 ± 6.5 yrs; 2 females, 7 males), referred to as the "PD group", and nine healthy older adults (67.7 ± 6.9 yrs; 7 females, 2 males), referred to as the "HO group", participated in this study. Each participant in the PD group was diagnosed with idiopathic PD having bilateral symptoms with impaired postural stability. Their Hoehn and Yahr scale was a score of 3 or 4 [41]. All participants were naïve to the purpose of the experiment.

Potential participants were excluded if they: 1) had a cognitive score less than 24 as determined by the Mini Mental State Examination (MMSE) [42]; 2) were not ready for physical activity as determined by the Physical Activity Readiness Questionnaire (PARQ); 3) had dyskinesia; 4) had severe distal sensory loss as determined by a 5.07g monofilament test; 5) were medically unstable (chest pain upon exertion, dyspnea); and 6) had any peripheral, neurological (other than PD for only the PD group), or musculoskeletal conditions as determined by a medical history questionnaire.

Informed consent was obtained from all participants prior to the study. The study was conducted in accordance with the Helsinki Declaration and approved by the Committee for the Protection of Human Subjects at the University of Houston.

C. Experimental Protocol

Participants in the PD group took their prescribed dose of dopaminergic medication to minimize tremor, bradykinesia, and muscle rigidity approximately 30 minutes prior to the start of the experimental session. It is worth noting that dopaminergic medication is not effective for treating postural instability [43]–[46], thus balance rehabilitation regimens have been advocated as a primary focus for improving postural stability for individuals with PD [47]–[51].

At the beginning of the experimental session, all participants in the PD and HO group were instrumented with the waist belt housing the IMU and four tactors. Their LOS in each A/P and M/L direction were obtained from body sway in degrees that corresponded to the furthest deviations of their body sway from a neutral starting point with respect to the ankle joint. All participants performed 12 familiarization trials (i.e., two coding schemes × two movement directions × three repetitions) to acclimate themselves to vibrotactile biofeedback during dynamic weight-shifting balance exercises, then they took a 5 min seated rest.

After the mandatory seated reset, all participants performed dynamic weight-shifting balance exercises as a function of the coding scheme and movement direction for a total of 20 trials (i.e., two coding schemes × two movement directions × five repetitions). The number of repetitions was determined based on our prior investigation [31]. The order of the 20 trials was randomized for each participant. During dynamic weight-shifting balance exercises, all participants were asked to stand on a firm surface with their arms held down at their sides, their feet hip-width apart, and their eyes opened. They were also instructed to move their bodies with respect to the ankle joint by locking their knees and hip joints. For the use of vibrotactile biofeedback, all participants were instructed to move the body away from the vibration until the vibration stops for the binary coding scheme or the intensity of the vibration is minimized for the continuous coding scheme. Each trial lasted less than 1 min, and consecutive trials were separated by approximately a 20 s rest period. In addition, a mandatory seated rest was provided to all participants after every ten trials.

After the completion of 20 trials, participants' LOS in each movement direction were re-measured to evaluate the effects of dynamic weight-shifting balance exercises with assistive vibrotactile biofeedback. The custom software recorded the target and participant's motion in degrees, the period of tactor activation, and the two sets of LOS values for each movement direction in text format for analysis.

D. Data and Statistical Analysis

Data analyses for the recorded data (i.e., target and participant motions and LOS) were performed using MATLAB (The MathWorks, Natick, MA). To characterize participants' ability to perform dynamic weight-shifting balance exercises as a function of the coding scheme and movement direction, two metrics were computed for each trial: cross-correlation

TABLE I
STATISTICAL ANALYSIS RESULTS OF THE LOS FOR GROUP (G), EXERCISE (E), AND THEIR INTERACTION. *STATISTICAL SIGNIFICANCE

Dependent variable	Effects	DF	F Value	Pr>F
A/P LOS	G	1, 32	3.460	0.685
	E	1, 68	231.141	0.002*
	G x E	1, 68	1.240	0.808
M/L LOS	G	1, 32	6.317	0.446
	E	1, 68	195.627	< 0.0001*
	G x E	1, 68	1.131	0.746

(XCOR) and position error (PE). XCOR quantitatively measures similarities of two time-series signals as a function of the angular displacement of the participant relative to the angular displacement of the target [31], [32]. The output of the XCOR analysis ranges between −1 and 1, where −1, 0, and 1 indicate perfect anti-phase similarity, complete lack of similarity, and perfect in-phase similarity, respectively, between the angular displacement of the participant and the angular displacement of the target. Since any negative values of the XCOR analysis were not observed across all participants, the output of the XCOR analysis is a positive value ranging between 0 and 1, where 1 indicates a perfectly matched motion. PE is computed as an average absolute difference between the target and participant's movements in degrees [31], [32].

Statistical analyses were performed using SPSS (IBM Corp., Armonk, NY). All dependent metrics (i.e., LOS, XCOR, and PE) were normally distributed for each direction, verified with Levene's test of equality of error variances. Statistical analysis consisted of an initial analysis and main analysis. In the initial analysis, the effects of the trial repetition were assessed for XCOR and PE using a repeated measures analysis of variance (ANOVA). Since the initial analysis indicated no significant effects on the trial repetition, the average of the five repetitions as a function of the coding scheme and movement direction for each individual were used for the main analysis. In the main analysis, a two-way ANOVA as a function of the movement direction was performed for all dependent metrics. For the LOS, the main effect of the group and exercise (pre and post exercise) as well as their interactions were assessed. For XCOR and PE, the main effect of the group and coding scheme as well as their interactions were assessed. In the main analysis, the main effects and interactions were tested using an $\boldsymbol{F}$-test. Additionally, a post hoc analysis using Sidak's method was performed to determine which factors influenced the main and interaction effects. The level of significance was set to $p < 0.05$.

III. RESULTS

Fig. 3 illustrates the LOS as a function of the group for each movement direction (i.e., A/P and M/L direction). Table I summarizes the results of the statistical analysis for LOS in the A/P and M/L direction. The two-way ANOVA indicated

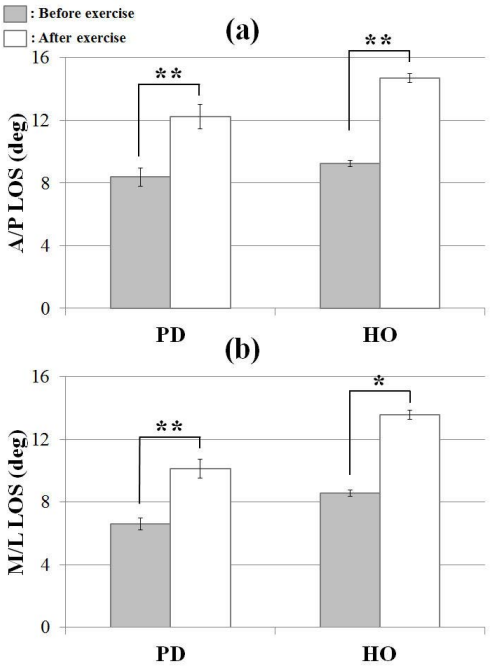

Fig. 3. Average LOS as a function of the group in the A/P (a) and M/L (b) direction before and after weight-shifting balance exercises with assistive vibrotactile biofeedback. The PD and HO indicates the PD group and healthy older group, respectively.

significant main effects of the exercise for both A/P and M/L directions. The post hoc analysis showed that LOS were significantly greater after the exercise than before the exercise regardless of the group and movement direction (A/P LOS: $p = 0.036$ for the PD group, $p = 0.008$ for the HO group; M/L LOS: $p = 0.008$ for the PD group, $p = 0.003$ for the HO group), indicating that LOS in both A/P and M/L directions were improved for both groups after the completion of 20 trials. However, the main effects of the group and interaction effects (i.e., group x exercise) for LOS in the A/P and M/L direction were not significant.

Fig. 4 shows representative sample data for one participant in each group during the A/P dynamic weight-shifting exercise as a function of the coding scheme. Table II summarizes the results of the statistical analysis for XCOR and PE in the A/P and M/L direction. Fig. 5 shows the XCOR analysis as a function of the group and coding scheme for each movement direction. The two-way ANOVA applied to the XCOR indicated significant main effects of the group and coding scheme regardless of the direction, whereas the interaction effects (i.e., group x coding scheme) were not significant. The post hoc analysis showed that the XCOR was greater with the continuous coding scheme than with the binary coding scheme for both groups regardless of the movement direction (A/P XCOR: $p = 0.002$ for the PD group, $p = 0.012$ for the HO group; M/L XCOR: $p = 0.002$ for the PD group, $p = 0.002$ for the HO group). In addition, pairwise comparisons indicated that the HO group had significantly greater XCOR values than the PD group regardless of the coding scheme and movement direction (A/P XCOR: $p = 0.008$ for the binary coding scheme, $p = 0.036$ for the

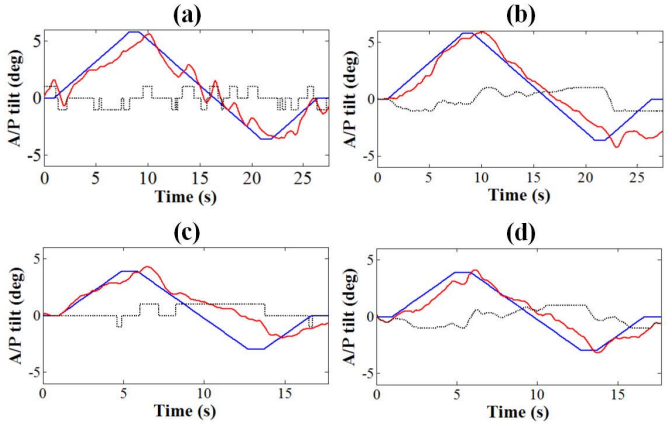

Fig. 4. Representative sample data. (a) One healthy older adult with the binary coding scheme. (b) One healthy older adult with the continuous coding scheme. (c) One PD individual with the binary coding scheme. (d) One PD individual with the continuous coding scheme. Solid blue and red lines represent the target motion and participant's motion, respectively. Dotted black lines represent the vibrotactile activation. For the binary coding scheme (i.e., (a) and (c)), 1, 0, and −1 indicates navel tactor on, tactor off, and spine tactor on, respectively. For the continuous coding scheme (i.e., (b) and (d)), 1, 0, and −1 indicates navel tactor on with its maximum intensity, tactor off, and spine tactor on with its maximum intensity, respectively.

TABLE II
STATISTICAL ANALYSIS RESULTS OF THE CROSS-CORRELATION AND POSITION ERROR FOR GROUP (G), CODING SCHEME (C), AND THEIR INTERACTION. *STATISTICAL SIGNIFICANCE

Dependent variable	Effects	DF	F Value	Pr>F
A/P XCOR	G	1,32	12.546	0.001*
	C	1,32	17.740	< 0.0001*
	G x C	1,32	0.194	0.663
A/P PE	G	1,32	49.557	< 0.0001*
	C	1,32	15.178	< 0.0001*
	G x C	1,32	0.002	0.961
M/L XCOR	G	1,32	17.603	< 0.0001*
	C	1,32	22.617	< 0.0001*
	G x C	1,32	0.003	0.955
M/L PE	G	1,32	96.223	< 0.0001*
	C	1,32	27.390	< 0.0001*
	G x C	1,32	0.057	0.813

continuous coding scheme; M/L XCOR: $p = 0.006$ for the binary coding scheme, $p = 0.005$ for the continuous coding scheme).

Fig. 6 depicts the PE analysis between the target and participant movements in both A/P and M/L directions as a function of the group and coding scheme. The two-way ANOVA indicated significant main effects of the group and coding scheme regardless of the direction. There were no significant interaction effects between the group and coding scheme (i.e., group x coding scheme). The post hoc analysis showed that the continuous coding scheme yielded significantly less PE than

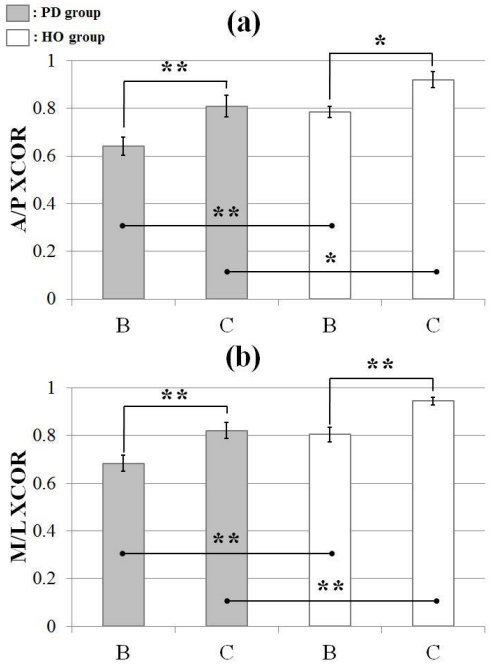

Fig. 5. Average XCOR as a function of the group and coding scheme in the A/P (a) and M/L (b) direction. The B and C indicates the binary and continuous coding scheme, respectively. Error bars indicate standard error of the corresponding average (*$p < 0.05$, **$p < 0.01$).

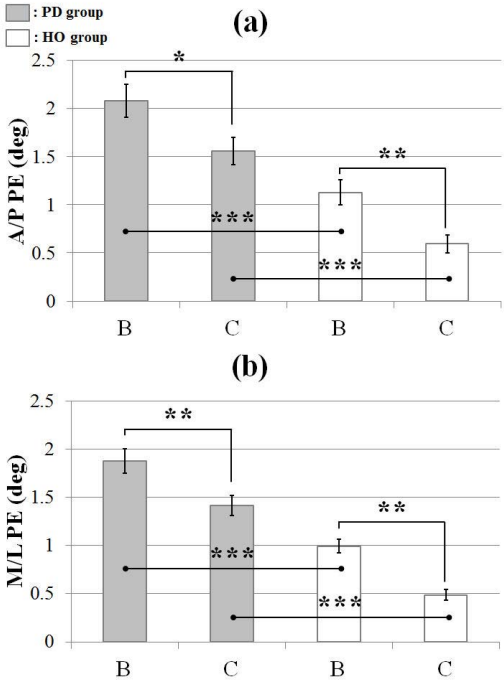

Fig. 6. Average PE as a function of the group and coding scheme in the A/P (a) and M/L (b) direction. The B and C indicates the binary and continuous coding scheme, respectively. Error bars indicate standard error of the corresponding average (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

with the binary coding scheme for both groups regardless of the movement direction (A/P PE: $p = 0.01$ for the PD group, $p = 0.009$ for the HO group; M/L PE: $p = 0.001$ for the PD group, $p = 0.001$ for the HO group). In addition, pairwise

comparisons indicated that the HO group had significantly less PE values than the PD group regardless of the coding scheme and movement direction (A/P PE: $p < 0.0001$ for the binary coding scheme, $p < 0.0001$ for the continuous coding scheme; M/L PE: $p < 0.0001$ for the binary coding scheme, $p < 0.0001$ for the continuous coding scheme).

IV. Discussion

The main finding of this work is that the continuous coding scheme produced significantly better performance than the binary scheme when both groups were performing dynamic weight-shifting balance exercises with assistive vibrotactile biofeedback regardless of the movement direction. Specifically, both groups had greater XCOR and less PE with the continuous coding scheme than with the binary coding scheme. The beneficial effect of the continuous coding scheme was independent of movement directions (i.e., A/P and M/L direction). We attribute these findings to the presence of error magnitudes delivered by the continuous coding scheme in real-time during dynamic weight-shifting balance exercises.

It is generally accepted that an error-driven process in the CNS plays a critical role in acquisition and adaptation of human motor movement skills [52]. In a feedforward internal model for motor task learning, movement errors detected by the sensory system is used to update the motor commands for subsequent actions [53]. Hence, it is postulated that the continuous coding scheme leveraged better directional correction of body sway than the binary coding scheme by providing continuous updates of motion errors, thereby resulting in better subsequent movements in real-time. Our findings are in agreement with improved motor performance and learning using continuous task-related feedback during upper limb exercises [54] and sensorimotor adaptation tasks [55].

We also found that the HO produced significantly better performance than the PD group as quantified by the XCOR and PE in both A/P and M/L directions regardless of the coding scheme. This result can be associated with the pathophysiology of PD (e.g., dopamine neuronal loss, changes in the cerebellum, and disruption of movement execution). PD is caused by the malfunction or death of certain nerve cells (or neurons) in the brain's substantia nigra, which produces a neurotransmitter (a.k.a., a dopamine in the basal ganglia) responsible for motor functions [56]. Prior computational and empirical studies have shown that the midbrain dopamine system and the basal ganglia are key cortical structures involved in error processing [57], [58]. Dopamine also modulates stimulus-response associations and carries predictive error signals to various parts of the brain for reinforcement learning [59]. It is well known that the cerebellum plays an important role in error-based motor learning [60] and formulating internal models for motor actions [61]. There is increasing evidence that the pathophysiology of PD may influence abnormal changes in the cerebellum (see [62] for review). More specifically, PD-related functional or morphological modulations in the cerebellum were identified, which may account for some motor symptoms of PD (e.g., rigidity, tremor, and gait disturbance). Furthermore, less accurate movement coordination observed in the PD group might be induced by disruption of movement execution including slow reaction time and movement time [63].

Finally, this study revealed that both groups of participants significantly improved LOS in both A/P and M/L directions after the completion of a small number of dynamic weight-shifting balance exercises (i.e., total of 20 trials). This result is in line with our previous investigation that dynamic balance exercises combined with biofeedback led to the improved LOS [31]. Interventions that contain components of dynamic weight-shifting balance exercises have been shown to improve postural stability in individuals with PD as well as older adults [3], [64]. Additionally, balance rehabilitation therapy with components of weight-shifting exercises demonstrated marked improvements over time in postural sway, gait speed, and Timed "Up & Go" for individuals following acute stroke [65]. It is likely that these balance rehabilitation program with components of weight-shifting exercises are effective as they target the individual physiologic systems involved in balance control, specifically the visual, vestibular, somatosensory, and musculoskeletal systems.

The limitations of the present study are a relatively small sample size, and an imbalanced gender distribution within and between the groups. In addition, exploring different thresholds for vibrotactile biofeedback and whether one coding scheme may result in more increase in the LOS than the other are worth further investigation. Despite the limitations, this study revealed the beneficial effects of the continuous coding scheme for a vibrotactile biofeedback paradigm and suggests that dynamic weight-shifting exercises combined with vibrotactile biofeedback can lead to improved postural stability and movement coordination for PD and elderly individuals. The study findings also have implications for the future design of vibrotactile biofeedback technology. To date, the binary coding scheme has been primarily used for vibrotactile biofeedback technology intended for balance-related applications [25]–[32]. However, the present study confirms that the continuous coding can provide better temporal aspects of the target motion and facilitate movement timing in targeting tasks than the binary coding scheme [66], [67]. The continuous coding scheme may also improve fidelity of smartphone-based vibrotactile biofeedback technology for home-based balance rehabilitation [28], [35], [68].

V. Conclusion

To the best of our knowledge, this is the first study to compare two different coding schemes (i.e., binary and continuous coding scheme) for a vibrotactile biofeedback paradigm during dynamic balance training exercises in individuals with PD and healthy elderly individuals. In both participant cohorts, a continuous coding scheme yielded a significantly better performance in terms of being able to mimic the targeted movement with less position error in both the A/P and M/L directions.

Our findings have promising implications in terms of maximizing the effects of error-driven motor learning and increasing performance on balance rehabilitation training combined with vibrotactile biofeedback. Future studies will investigate

the effects of different thresholds for vibrotactile biofeedback, two vibrotactile coding schemes on the LOS, and long-term balance rehabilitation training guided by vibrotactile biofeedback and the carry-over effects of a long-term use of biofeedback technology on gait performance, fear of falling, and daily activity performance in balance-impaired individuals (e.g., individuals with PD, stroke survivors, elderly individuals, and individuals with vestibular dysfunction).

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