

Ambulatory monitoring of freezing of gait in Parkinson's disease

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Abstract

Freezing of gait (FOG) is common in advanced Parkinson's disease (PD), is resistant to treatment and negatively impacts quality of life. In this study an ambulatory FOG monitor was validated in 11 PD patients. The vertical linear acceleration of the left shank was acquired using an ankle-mounted sensor array that transmitted data wirelessly to a pocket PC at a rate of 100 Hz. Power analysis showed high-frequency components of leg movement during FOG in the 3–8 Hz band that were not apparent during volitional standing, and power in this 'freeze' band was higher ($p=0.00003$) during FOG preceded by walking (turning or obstacles) than FOG preceded by rest (gait initiation). A freeze index (FI) was defined as the power in the 'freeze' band divided by the power in the 'locomotor' band (0.5–3 Hz) and a threshold chosen such that FI values above this limit were designated as FOG. A global threshold detected 78% of FOG events and 20% of stand events were incorrectly labeled as FOG. Individual calibration of the freeze threshold improved accuracy and sensitivity of the device to 89% for detection of FOG with 10% false positives. Ambulatory monitoring may significantly improve clinical management of FOG.

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1. Introduction

Parkinson's disease (PD) results from a progressive loss of dopaminergic and other sub-cortical neurons (Braak et al., 2004), manifested clinically as resting tremor, bradykinesia, rigidity, a forward stooped posture, postural instability and freezing (see Morris et al. (2001)). Levodopa (LD), the metabolic precursor to dopamine, is commonly used to manage the motor symptoms of PD by replacing endogenous dopamine at the striatum. However, freezing of gait (FOG), a transient block of movement (particularly when initiating gait, turning, or negotiating an obstacle) is often resistant to dopamine replacement therapy (Bloem et al., 2004). FOG is generally regarded as a 'late' feature of PD associated with disease duration and severity (Bloem et al., 2004; Giladi et al., 2001b; Macht et al., 2007), although up to 26% of patients in the early stages of the disease (not yet administered levodopa) were found to have experienced freezing (Giladi et al., 1992, 2001a,b). A survey of 6620 patients found that 10% of respondents with mild PD symptoms and 80%

of those severely affected regularly experienced freezing (Macht et al., 2007).

FOG represents a common cause of falls in PD (Bloem et al., 2004), interferes with daily activities, and significantly impairs quality of life (de Boer et al., 1996); yet management of FOG is difficult and often ineffective (Fahn, 1995). Clinical assessment of FOG is largely based on subjective patient reports, such as the Unified Parkinson's Disease Rating Scale (UPDRS), Activities of Daily Living (ADL) part 15 (Fahn et al., 1987), which rates freezing on a scale from 0 (none) to 4 (frequent falls from freezing) based on patient history. A more comprehensive (but still subjective) FOG questionnaire was recently validated (Giladi et al., 2000). FOG is difficult to elicit in a routine clinical examination, typically requiring a complex trajectory with multiple turns and obstacles to provoke freezing (Schaafsma et al., 2003). There exists no objective method for identifying FOG outside of the clinic.

The underlying pathology of FOG is unknown. A phenomenological study using video analysis has shown that FOG is often associated with a 'trembling' of the legs in an effort to overcome the block (Schaafsma et al., 2003), speculated to be an atypical form of action legs dystonia or dystonic tremor. A laboratory study of insole pressure demonstrated an increase in

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high-frequency (2–6 Hz) components during freezing that may represent an attempt to overcome the block, or the output of multiple ‘pathologic neural networks’ that interfere with the normal locomotor pattern (Hausdorff et al., 2003b). Bloem et al. (2004) have similarly speculated that these high-frequency leg movements are generated by ‘misfiring oscillators’ that force the legs to move too fast for effective stepping during FOG. Studies of the steps prior to freezing have shown a cumulative loss of stride length and accelerated cadence (Nieuwboer et al., 2001), and abnormal timing of tibialis anterior and gastrocnemius muscle activation (Nieuwboer et al., 2004), suggesting a central deficit in the rhythmic control of gait is fundamental to FOG. Moreover, Hausdorff et al. (2003c) have suggested that this inability to regulate cadence is a continuous gait disturbance in PD patients with FOG, rather than a paroxysmal phenomenon related to freezing.

In the current study we describe a device for ambulatory monitoring of FOG using the frequency characteristics of vertical leg movement. We hypothesized that the ‘trembling’ of the legs during FOG observed from video recordings (Schaafsma et al., 2003) and insole pressure (Hausdorff et al., 2003b) would also be apparent in the vertical linear acceleration of the shank. We have previously developed an ambulatory stride length monitor for PD (Moore et al., 2007), and here we extend the capabilities of this device to detection of freezing events and demonstrate its effectiveness in a pilot study of 11 patients with advanced PD.

2. Methods

Eleven participants (nine males) diagnosed with idiopathic PD (UK PD Society Brain Bank diagnostic criteria (Hughes et al., 1992)) were recruited by a movement disorders specialist at the Parkinson’s Disease Center and Movement Disorders Clinic (PDCMDC) at Baylor College of Medicine (Table 1). All patients reported a clinical history of FOG, and had no known non-dopaminergic lesions or cognitive impairment. Age ranged from 45 to 72 years (61.5 years [S.D. 9.6]), age at onset of PD from 24 to 60 years (44.3 years [S.D. 12.2]), time since onset from 6 to 28 years (17.2 years [S.D. 7.2]), and Hoehn and Yahr

(H&Y) stage III–IV (‘off’ state). All participants were taking an oral levodopa/carbidopa combination, with the morning levodopa dose ranging from 100 to 450 mg (182 mg [S.D. 106]) and total daily dose from 500 to 2350 mg (1190 mg [S.D. 643]). Leg movement data were also obtained from 10 healthy controls aged from 35 to 68 years (46 years [S.D. 10.9]). The study was approved by the Institutional Review Boards at the Mount Sinai School of Medicine and Baylor College of Medicine and Affiliated Hospitals, and was performed in accordance with the ethical standards of the 1964 Declaration of Helsinki. Participants gave informed consent prior to their inclusion in the study.

Patients arrived 8:00 a.m. at the PDCMDC without having taken their usual morning PD medications (time since previous dopaminergic medication administration was at least 12 h), in an ‘off’ state. Participants walked without assistance at a self-determined pace around a series of internal corridors with at least two 180° turns, starting and ending in a conference room where they were required to negotiate a narrow doorway and three obstacles (a small table and two chairs). Subjects were also asked to stand for 10 s at the end of each walking trial to obtain a baseline for leg movement for comparison with FOG. Patients then took their usual morning dose of PD medications (Table 1) and periodically repeated the walking task (every 13.2 min [S.D. 4.5] on average) over a 90 min epoch post-administration. Distance walked was dependent on patient ability, ranging from 1 to 90 m (49 m [S.D. 28]) when ‘off’ and from 35 to 94 m (61 m [S.D. 20]) in the ‘on’ state. Data collection was terminated at 90 min or earlier if the ‘on’ state had been reached over at least two periods of locomotor activity.

‘Off’ and ‘on’ states were determined from subject feedback and a brief clinical evaluation by a neurologist familiar with the patients; all subjects were clinically ‘off’ prior to levodopa administration and had reached an ‘on’ state by the end of testing. All walking trials were recorded on a digital video camera and episodes of freezing of gait were identified from the video records by a movement disorders specialist.

During walking, movement of the left leg was measured using a novel ambulatory device developed by the authors (Moore

Table 1
Patient characteristics

Subject ID	Age (years)	Onset (years)	Time since Dx (years)	LD (morning) (mg)	LD (total) (mg)	H&Y ‘off’	H&Y ‘on’	Adjunct PD meds
6 ^F	65	42	23	100	800	III	II	Tolcapone
7 ^F	45	24	21	100	600	IV	II	Tolcapone
9 ^F	65	37	28	100	1250	III	III	–
10	65	54	11	250	1900	III	II	Pramipexole
11	72	50	22	450	2350	IV	III	Pramipexole
12 ^F	68	52	16	150	1750	IV	III	Pramipexole
13	66	60	6	150	600	III	II	Entacapone, pramipexole
14	51	42	9	250	1250	III	II	Entacapone, ropinirole
15 ^F	60	35	25	200	1600	III	II	Ropinirole, deprenyl, amantadine
17 ^F	47	30	17	100	500	IV	III	Pramipexole
19 ^F	72	61	11	150	500	III	II	–

An ^F next to the subject ID indicates that this patient experienced FOG during the study.

et al., 2007). An Inertial Measurement Unit, 9 V battery and Bluetooth serial transmitter were mounted around the left shank (just above the ankle) using an elasticized strap and Velcro. The stride monitor was unobtrusive (weighing less than 130 g) and did not interfere with locomotion; a critical point as distractions significantly increase gait variability in PD (Hausdorff et al., 2003a). Vertical linear acceleration and pitch angular velocity of the left leg were transmitted wirelessly at a rate of 100 Hz to a Pocket PC (PDA) carried by an investigator, who typically walked 5 m behind the participant and operated the video camera. After each walking trial leg movement data was processed using custom analysis software to determine periods of locomotion (from vertical linear acceleration of the shank) and the length of every stride taken (using angular velocity of the shank in the sagittal plane) (Moore et al., 2007). Synchronization of leg movement data with the video recordings (to within one video frame; ~ 33 ms) was achieved by obtaining an image of the PDA screen as data logging was initiated.

Episodes of FOG were identified from the frequency spectra of vertical leg acceleration (see Fig. 2). A ‘locomotor’ band was defined as the frequency components from 0.5 to 3 Hz, and a ‘freeze’ band from 3 to 8 Hz. A freeze index (FI) at time t was defined as the square of the area under the power spectra of a 6 s window of data (centered at time t) in the ‘freeze’ band, divided by the square of the area under the spectra in the ‘locomotor’ band. This minimized the influence of high-frequency harmonics (>2 Hz) during walking on freeze detection. The derivations of the locomotor and freeze bands, and the width of the sliding window used to calculate FI, are described below.

3. Results

Seven subjects experienced a total of 46 FOG events (Fig. 1) identified from video recordings (range 2–17 per subject; mean 6.6 [S.D. 5.1]; Table 1—denoted by ^F next to subject ID); four subjects did not freeze. The 46 FOG events were categorized (Fig. 1A) as gait initiation (15), turning (20) or obstacles (11). Almost half of FOG events (22/46; 48%) occurred prior to levodopa administration (Fig. 1A), and virtually all FOG (45/46; 98%) occurred within 1 h of taking medication. The length of a FOG event ranged from 2 to 128 s (20.3 s [S.D. 22.4]), with 50% of FOG episodes lasting 10 s or less. The majority of freeze events (85%) were under 30 s duration (Fig. 1B). There was no effect of levodopa administration (pre-LD 21.2 s [S.D. 28.0]; post-LD 19.5 s [S.D. 16.8]; $p=0.7$) or the type of FOG (initiation 25.7 s [S.D. 35.4]; turning 15.3 s [S.D. 10.7]; obstacle 26.2 s [S.D. 16.3]; $p=0.34$) on the duration of a freeze event.

Data from a typical PD participant (subject 6) 10-min after levodopa administration illustrate the frequency characteristics of vertical shank acceleration during volitional standing, FOG and walking. When experiencing a freezing episode a ‘trembling’ of the leg was observed, reflected in the power spectra of vertical leg movement with high-frequency components in the 2–6 Hz band (Fig. 2B and C) that were not apparent when standing (Fig. 2A). During walking (Fig. 2D) the power spectrum of shank vertical linear acceleration exhibited highly tuned dominant components at the stride (~ 1 Hz) and step (~ 2 Hz) frequen-

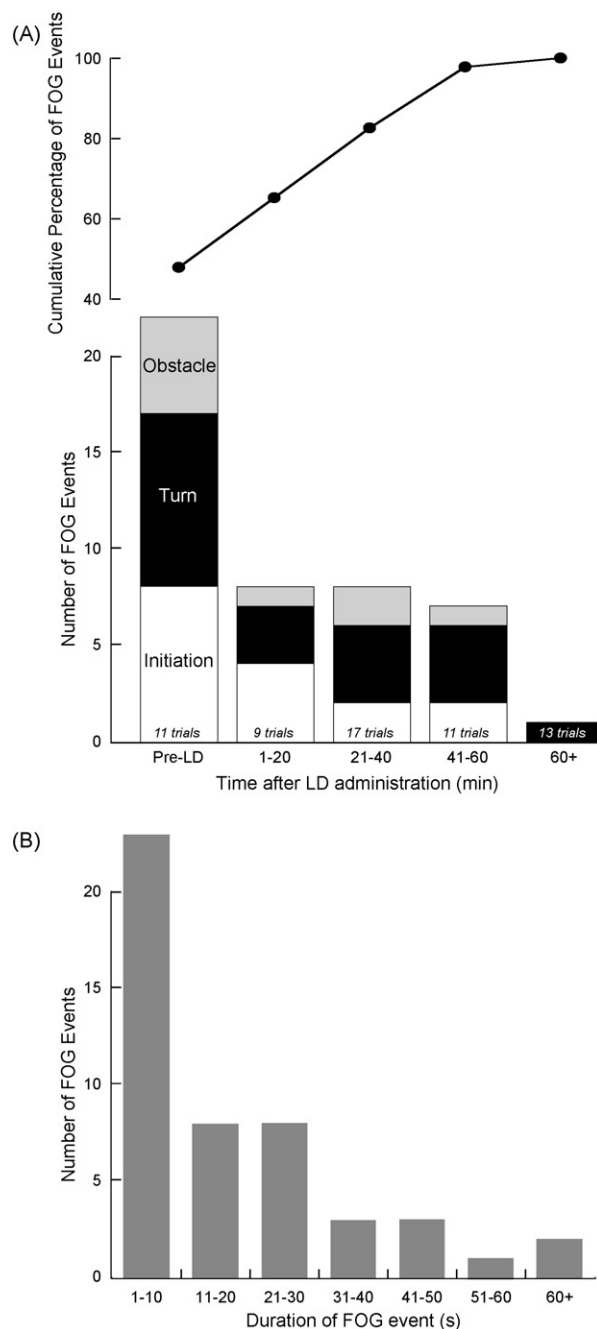


Fig. 1. (A) Cumulative percentage of FOG relative to time after levodopa administration (upper plot) and number and category of FOG events (initiation, turning or obstacle; lower plot) relative to time after levodopa administration. Almost half of FOG events occurred prior to ingesting medication, and 98% occurred within 60 min. (B) Distribution of FOG duration; 50% of FOG events were 10 s or less, with 85% lasting under 30 s.

cies (plus higher-frequency harmonics), comparable with that observed in healthy controls (MacDougall and Moore, 2005).

A ‘locomotor’ band, which included the stride and step frequencies (see Fig. 2D), was defined as 0.5–3 Hz based on the frequency characteristics of gait in the 11 subjects. Mean step frequency (cadence) in the ‘off’ state was 1.9 Hz (S.D. 0.63), ranging from a slow 0.6 Hz shuffling gait to 3.2 Hz during festination. A ‘freeze’ band was defined as 3–8 Hz and contained

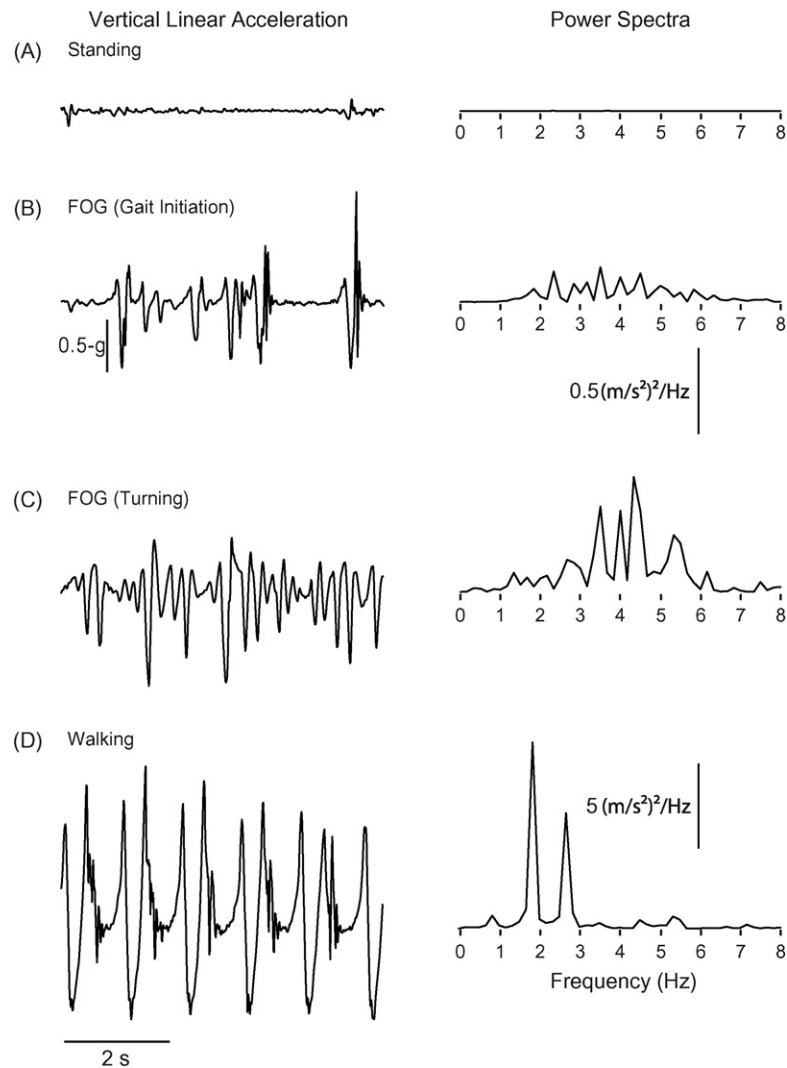


Fig. 2. Vertical linear acceleration of the left shank (6 s of data) and corresponding power spectra in a patient with advanced PD (subject 6) 10-min after levodopa administration. (A) During volitional standing there was minimal movement. (B) and (C): during FOG a high-frequency 'trembling' of the leg was observed with components in the 2–6 Hz band that were not present when standing. (D) The vertical movement of the leg during walking exhibited highly tuned components at the stride (~1 Hz) and step (~2 Hz) frequencies, with higher frequency harmonics.

the majority of high-frequency acceleration components during FOG (see Fig. 2B and C). The frequency characteristics of vertical leg movement during FOG observed in subject 6 (Fig. 2) were consistent across all seven subjects who experienced FOG (Fig. 3). The power in the freeze band was significantly higher ($p = 10^{-11}$) during FOG than when standing (Fig. 3A; red trace – FOG; green trace – standing). There was no significant difference in freeze band power during turning and when encountering an obstacle ($p = 0.74$), thus power spectra for these two FOG subtypes were pooled (Fig. 3B – orange trace). Power in the 3–8 Hz band during freezing when turning or encountering an obstacle was higher ($p = 0.00003$) than FOG during gait initiation (Fig. 3B). There were local maxima in the frequency spectra of FOG during turns and obstacles at 3, 4–5 and 5–7 Hz (Fig. 3B – orange trace), whereas local maxima were less obvious during gait initiation (Fig. 3B – blue trace).

Utilizing the freeze index (FI; a continuous dimensionless value defined in Methods above) it was possible to identify FOG

events during free ambulation. Data from subject 6 illustrate the technique (Fig. 4). Ten minutes after levodopa administration the subject walked approximately 50 m (Fig. 4A), starting from a conference room and walking along a corridor with two 180° turns, then returning to the room and negotiating a number of obstacles (a small table and two chairs). This subject experienced four FOG events: (1) when initiating gait, (2) and (3) when turning and (4) when encountering an obstacle (Fig. 4A and B). Fifty-five minutes after levodopa administration the subject was walking freely with no FOG (Fig. 4D). High-frequency components in the vertical leg acceleration during freezing (Fig. 4B – blue trace) were reflected in the FI (Fig. 4C – red trace). A freeze threshold for this subject (0.1) was calculated as the mean (0.04) plus one S.D. (0.06) of the peak FI from nine epochs of volitional standing. Application of this threshold enabled FOG events to be distinguished from locomotion and standing as peaks in the FI above 0.1 (Fig. 4C and E – green dashed line and shaded region).

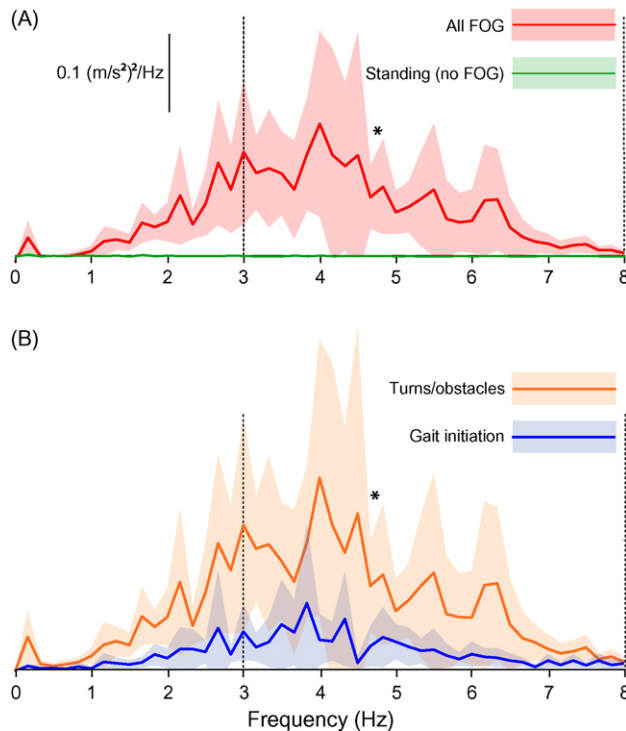


Fig. 3. (A) Frequency spectra from all 46 FOG events (seven subjects; mean and 90% CI—red trace) and during 50 periods of volitional standing (11 subjects; mean and 90% CI—green trace). The power in the freeze band (3–8 Hz) was significantly higher during FOG. (B) Frequency spectra from FOG when turning or encountering an obstacle (31 events from seven subjects—orange trace) and during gait initiation (15 events from six subjects—blue trace). The power in the freeze band when FOG was preceded by movement (turning and obstacles) was significantly higher than when starting from rest (gait initiation).

The width of the sliding window (6 s) used to calculate the power spectra of vertical leg movement for the FI was based on the distribution of FOG duration (Fig. 1B), which revealed 30% (14/46) of freezing events lasted 6 s or less and 15% (7/46) were under 4 s duration. An empirical analysis determined that the optimal window width was approximately twice the duration of the shortest FOG event to be detected. Increasing the window size acted as a low-pass filter and reduced the sensitivity of the FI in identifying short-duration freeze events (Fig. 5).

Across the seven subjects who experienced freezing peak FI during FOG ranged from 0.05 to 125 (7.5 [S.D. 22.1]), and when standing (50 events from all 11 subjects) peak FI ranged from 0.01 to 1.9 (0.12 [S.D. 0.35]). Due to the large variation in order of magnitude the FI was normalized by multiplying by 100 and taking the natural logarithm; normalized peak FI during FOG ranged from 1.6 to 9.4 (4.3 [S.D. 2.0]), and was significantly higher than when standing (range 0 to 5.2; 1.3 [S.D. 1.4]; $p = 4 \times 10^{-10}$). Application of the freeze threshold derived from subject 6 (Fig. 3C; 0.1, normalized value 2.3) to all 11 subjects detected 36 (78.3%) of the 46 FOG events; i.e., peak FI exceeded the global threshold of 2.3. Of the 50 periods of volitional standing from all 11 subjects, 10 (20.0%) were erroneously marked as FOG. However, establishing an individual FI threshold for each subject (using the technique described for subject 6 above) improved the accuracy and sensitivity of the freeze monitor.

The individual (normalized) threshold ranged from 2.3 to 4.4 ($N = 11$; mean 2.9 [S.D. 0.9]), and increased FOG detection to 41 of the 46 events (89.1%) and decreased false positives to 5 of 50 stand events (10.0%). Mean normalized FI during standing in 10 healthy control subjects was an order of magnitude smaller than the lowest freeze threshold (2.3) at 0.4 (S.D. 0.6).

Festination, a propulsive shuffling gait common in advanced PD, was observed in one subject (17) in the ‘off’ state (Fig. 6). Festinating gait was characterized by small, shuffling strides (~20 cm) (Fig. 6C), and a high step frequency of 3.2 Hz (at the upper-limit of the locomotor band) with significant harmonics in the 3–8 Hz freeze band (Fig. 6B). However, there was still sufficient power in the locomotor band (the stride frequency at 1.6 Hz) to distinguish FOG from festination using the FI (Fig. 6C).

4. Discussion

The results of this study demonstrate the feasibility of discriminating FOG from locomotion or volitional standing using the frequency spectra of shank vertical linear acceleration. Freezing when initiating gait, turning or encountering an obstacle was accompanied by high-frequency components in the 3–8 Hz (freeze) band of vertical leg movement, a reflection of the ‘trembling’ observed during FOG in both the current and previous studies (Hausdorff et al., 2003b; Schaafsma et al., 2003). A total lack of movement (akinesia) was not observed, consistent with the low incidence reported previously (Schaafsma et al., 2003). A freeze index (FI) was defined as the ratio of power in the freeze band divided by power in the locomotor (0.5–3 Hz) band, using the fact that during FOG power is concentrated in the freeze band, whereas volitional activity exhibited significant power below 3 Hz (MacDougall and Moore, 2005). Peaks in the FI exhibited a strong correlation with FOG identified from video recordings; 78% of freeze events were detected using a global ‘one-size-fits-all’ threshold for the FI, and FOG discrimination increased to 89% when the freeze threshold was calibrated for each subject.

The delineation between the locomotor and freeze bands is critical in calculation of the FI. In the current study 3 Hz proved a suitable breakpoint, identifying FOG in the presence of high-frequency (3.2 Hz) festinating gait. The only published study to characterize the frequency characteristics of FOG (from insole pressure) defined a similar power band for FOG (3–6 Hz) and found that less than 5% of power during locomotion in PD patients was within this range (Hausdorff et al., 2003b). A study of cadence during festination in PD patients with a history of freezing reported values less than 3 Hz (2.8 Hz [S.D. 0.2]) (Nieuwboer et al., 2001). Step frequencies above 3 Hz are certainly possible and may increase the FI above the freeze threshold. However, festinating gait could still be differentiated from FOG using the RMS magnitude of vertical leg acceleration (Fig. 6A), which is considerably larger during locomotion than when stationary (Moore et al., 2007). Moreover, the spread of spectral power into the freeze band during festination may be indicative of the close linkage with FOG proposed by Nieuwboer et al. (2001). The width of the sliding window used to calculate

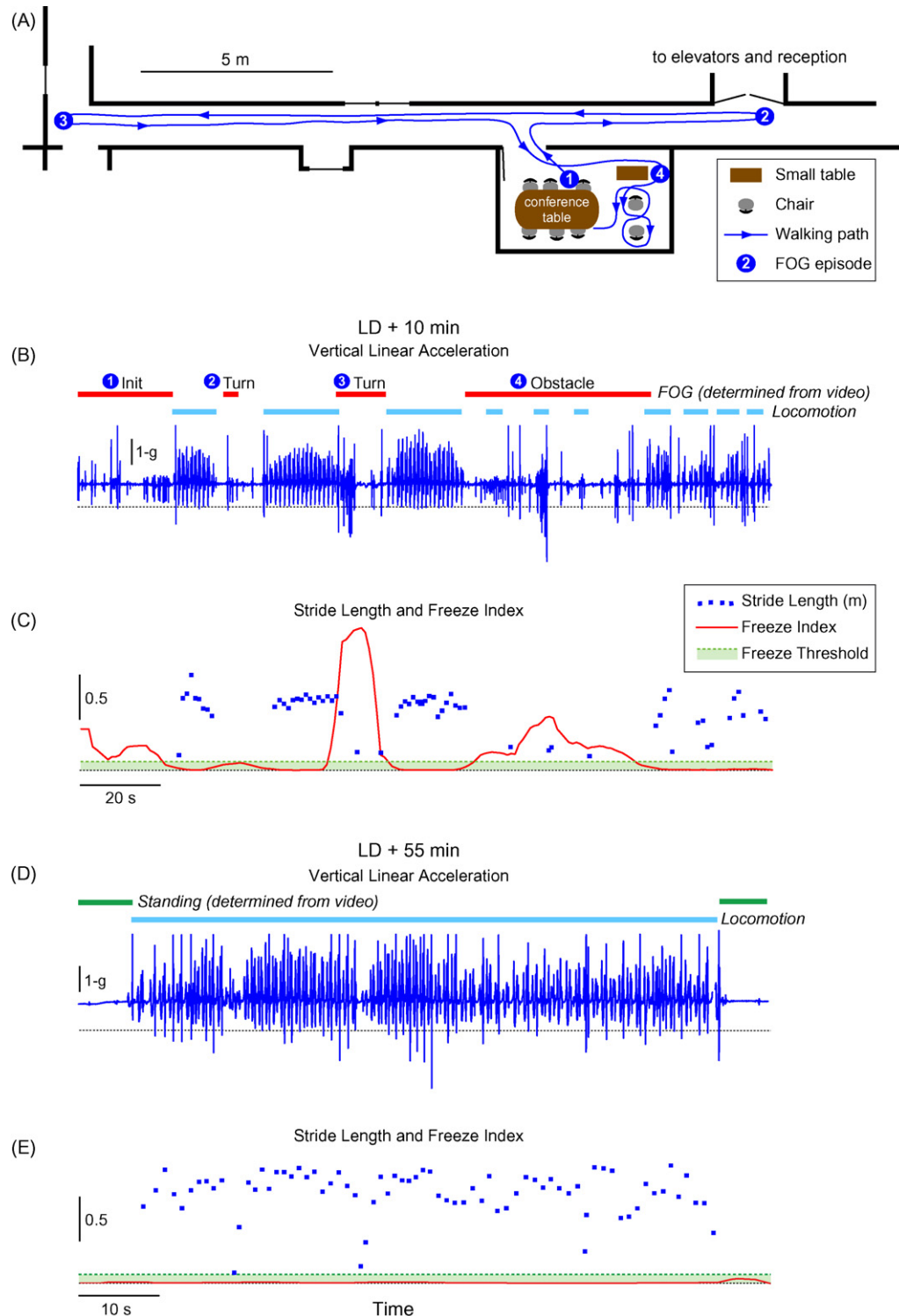


Fig. 4. Data from a patient with advanced PD (subject 6) demonstrates the FOG detection algorithm. (A) Approximate path taken by the subject 10-min post levodopa administration. This subject had four FOG events; when initiating gait, at each 180° turn in the corridor, and when negotiating an obstacle (small table). (B) Vertical linear acceleration of the left shank during the trial shown in (A). Red bars above the data indicate freezing episodes as determined from video recordings; light blue bars indicate periods of walking (determined from vertical acceleration (Moore et al., 2007)). During FOG there was a high-frequency ‘trembling’ of the leg apparent in the acceleration data. (C) The freeze index (FI—red trace) was calculated from the power in the freeze band (3–8 Hz) divided by power in the locomotor band (0.5–3 Hz). Large peaks occurred during FOG. A ‘freeze’ threshold could distinguish between FOG and periods of volitional standing. Stride length (blue squares) was also calculated from angular velocity and linear acceleration of the leg (Moore et al., 2007). (D) Vertical linear acceleration of the leg when following a similar trajectory as in (A) 55-min after levodopa administration. Green bars above the data indicate periods of volitional standing (not FOG) identified from the video recording. (E) FI during locomotion and standing was below the freeze threshold.

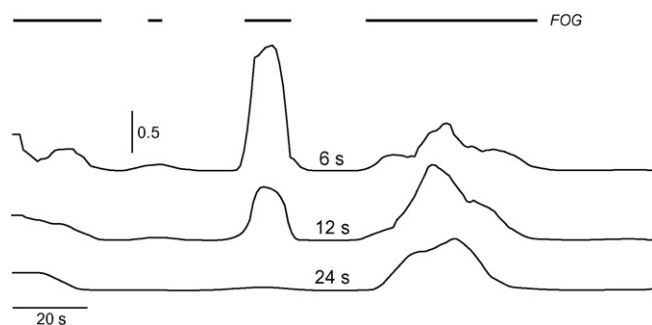


Fig. 5. Effect of the width of the sliding window used to calculate the freeze index (FI) using the movement data of subject 6 10-min post-levodopa administration (see Fig. 4A–C). Black bars at the top of the figure represent four FOG episodes determined from video recordings. The three traces represent FI calculated with a window of (from top to bottom) 6, 12 and 24 s width. Increasing window width acted as a low-pass filter and reduced the sensitivity of the FI to short-duration freeze events.

the power spectrum of vertical leg acceleration (and thus the FI) was set at 6 s in the current study, based on the finding that half of FOG events lasted 10 s or less. A similar distribution of freeze duration has previously been reported (Schaafsma et al., 2003).

The magnitude of the ‘global’ freeze threshold used to detect FOG in the current study was based on a small sample of patients, and larger studies accounting for age, age-at-onset, disease duration, severity and PD-related medications are required to determine the validity of this concept. Given the large inter-subject variation in the amplitude of power spectra for vertical body movement during locomotion (even in healthy subjects (Hirasaki et al., 1999; MacDougall and Moore, 2005)) individual calibration to adjust the threshold based on the relative magnitude of the FI during FOG and volitional activity is likely to be required in practice.

No participants exhibited peak-dose dyskinesias (which typically occur more than 60 min after levodopa administration) during data acquisition. Peak-dose dyskinesias primarily affect the upper part of the body (the face, neck and trunk) (Luquin et

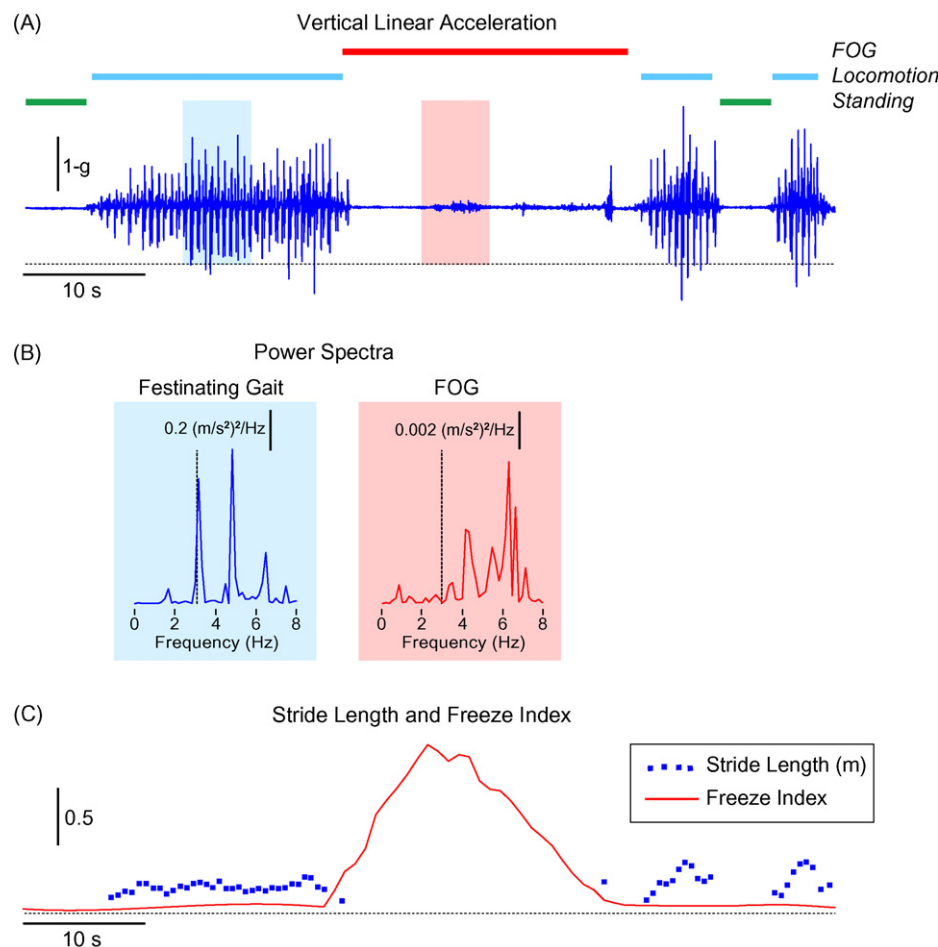


Fig. 6. Effect of festination on freeze detection. (A) Vertical leg acceleration data from subject 17 prior to levodopa administration. The red bar above the data indicates a FOG event (turning) determined from the video recording. Light blue bars signify locomotion, and green bars periods of volitional standing. The blue shaded region designates a 6 s epoch of festinating gait; the red shaded region is 6 s of data during FOG. (B) Power spectra of acceleration (6 s of data) during festination (blue) and FOG (red) from the shaded regions in (A). Note the step frequency (at 3.2 Hz significantly larger than the mean of 1.9 Hz for this group) and large high-frequency harmonics in the freeze band (3–8 Hz) during festinating gait. During FOG most of the power was concentrated in the freeze band. (C) Stride Length and Freeze Index. This subject exhibited small (~20 cm) shuffling strides. Despite the high-frequency harmonics during festination the FI could still distinguish FOG from gait and volitional standing.

al., 1992), and tend to be choreic in nature (Marsden et al., 1982) with primary frequency components below 3 Hz (Carroll et al., 2004). The less common diphasic dyskinesia, which occurs at the beginning and end of the levodopa cycle and manifests as slow, stereotyped, repetitive movements of the lower limbs (Marconi et al., 1994; Marsden et al., 1982), was not observed. We have previously quantified diphasic dyskinesia at the shank in a patient with advanced PD (H&Y III) and found the frequency of leg movements to be concentrated in the 1–1.5 Hz range (Moore et al., 2007). Peak-dose dyskinesias occur when freezing is uncommon, and the low-frequency nature of both peak-dose and diphasic dyskinesias (below the 3 Hz limit of the freeze band) suggest that neither is likely to affect identification of FOG.

A novel result was the significantly higher power in the freeze band during turning or negotiating an obstacle relative to gait initiation, suggesting a difference in vertical leg movements dependent on whether the freeze event was preceded by walking (turning or obstacles) or the subject was at rest (initiation). The local maxima observed in the power spectra of FOG leg movements during turning and obstacles may provide some support for the hypothesis that multiple ‘misfiring oscillators’, interfering with the normal locomotor rhythm, are involved in FOG (Bloem et al., 2004; Hausdorff et al., 2003b; Nieuwboer et al., 2001, 2004). The peak at 3 Hz may reflect an increased cadence prior to freezing (Nieuwboer et al., 2001) or a higher-frequency harmonic of stepping (MacDougall and Moore, 2005) (see Fig. 2D), still present despite the motor block. The maxima between 4 and 5 Hz is consistent with the frequency of resting tremor in PD, and peaks in the 5–7 Hz band have been associated with PD postural tremor (Findley et al., 1981; O’Suilleabhain and Matsumoto, 1998). A frequency analysis of PD wrist tremor observed combined spectral peaks around 4.5 Hz and 6 Hz in some patients, with EMG activity suggesting each tremor frequency had a unique underlying oscillating mechanism (Findley et al., 1981). However, the similarity of the dominant frequencies of vertical leg movement during FOG at 4–5 and 5–7 Hz to those observed in resting and postural PD tremor may well be coincidental. Jankovic et al. (1990) defined two PD clinical subtypes as tremor dominant (TD) and postural instability and gait difficulty (PIGD), with the latter group having a faster disease progression and a higher risk of developing FOG (Giladi et al., 2001a). In fact, tremor as the initial motor symptom and high scores on the UPDRS tremor items were strongly associated with a decreased risk of FOG at any stage of the disease (Giladi et al., 2001a). In this study all subjects were classified as PIGD. Nevertheless, the frequency characteristics of leg movement during FOG preceded by locomotion suggest multiple oscillating inputs, one of which may be related to cadence.

Despite all 11 subjects reporting a clinical history of FOG, only 7 experienced freezing during the experiment. Stress, attention and distractions have both positive and negative influences on freezing (Bloem et al., 2004), and the controlled environment of a research study may have reduced the likelihood of FOG in the subjects who did not freeze (Nieuwboer et al., 2001, 2004); alternatively, this group may have over-reported the incidence of FOG. Either case demonstrates the need for objective long-term

monitoring of FOG during natural daily activity. Community monitoring of stride length in PD patients over extended periods (6 h) demonstrated that leg movement during volitional activities exhibited significant power in the locomotor band (Moore et al., 2007), consistent with our previous study of the frequency characteristics of movement in healthy subjects over 10-h epochs (MacDougall and Moore, 2005). This suggests that the FI technique could be used to distinguish FOG from active movement outside of the controlled environment of the clinic. However, the frequency characteristics of passive leg motion (e.g., as experienced as a passenger in a car, bus, or train) need to be determined. Heuristics may prove useful in identifying freezing of gait; a peak in the FI that is not preceded or followed by locomotion is unlikely to be FOG. Further studies are required to validate community freeze monitoring.

The intractable nature of FOG may be related, in part, to difficulty in assessing its characteristics and incidence. Evaluation of ‘open-loop’ treatment options, without objective feedback on the influence of therapy on freezing, is likely to be ineffective. An ambulatory freeze monitor could provide this feedback, and help to improve management of FOG in PD.

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