6th Annual International IEEE EMBS Conference on Neural Engineering
San Diego, California, 6 - 8 November, 2013

Characteristics of Gait Freezing: Possibilities for Rehabilitation *

Fariborz Rahimi, *Member, IEEE,* Si Yu Xian, Mehdi Delrobaei, *Member, IEEE,* Mandar Jog, MD

Abstract— **Freezing of gait is a debilitating symptom that affects mobility in Parkinson disease (PD) patients. In this study, we examined mean center of pressure (CoP) for patients during freezing and compared them against mean CoP during standing and walking. Patients experienced a significantly forward CoP (p<0.01) during freezing than standing and walking, which is associated with an increased risk of falling. Absolute mean CoP differences between left and right foot represent an out of phase CoP profile during freezing. These findings can be used to suggest new strategies for fall prevention as well as freeze breaking strategies.**

I. Introduction

Freezing of gait (FOG) is a distinct component of gait dysfunction in Parkinson disease (PD) and is currently defined as: "Brief, episodic absence or marked reduction of forward progression of the feet despite the intention to walk, including start hesitation, turn and destination hesitation"[1].

Freezing of gait is most associated with disease duration and is a major risk factor for falls[2]. Fear of falling, combined with difficulty in ambulation reduce the mobility of patients with this debilitating condition[3].

Current rehabilitation strategies are focused on sensory cueing for freeze breaking[4]. Nieuwboer et al. assessed various methods of cueing and found brief reduction in freezing severity, but this did not translate into long-term benefit [5]. So far, there are no rehabilitation strategies that targets bio-mechanical properties of freezing of gait.

Recent development in sensor technology has allowed for in depth kinematic and bio-mechanical analysis of this condition. These technologies are now wire-less and cause minimal to no interference with walking. This allows an excellent measure of gait in a patient population in the laboratory and in the home environment. It is now possible for wearable sensors to be integrated into a treatment routine through various means, including automatic detection, personalized data for rehabilitation strategies, as well as gathering biomechanical information with respect to the overall mobility of patients.

Characteristics of Freezing of gait have been extensively studied kinematically for detection of freezing[6]. These studies employ accelerometers and inclinometers on different parts of the body as means for automatic detection[7]. However, freezing characteristics from a foot pressure perspective has never been explored. This is important as a significant proportion of biomechanical abnormality during freezing may be measured by foot pressure changes. Using this technology, we aim to show that freezing has specific bio-mechanical tendencies among patients which may allow personalized rehabilitation strategies to decrease duration of freezing and risk for falls. In addition, our findings may be implemented to improve and strengthen current methods of cueing rehabilitation and automatic detection of FOG.

II. Methods

A. Study Subjects

Eighteen patients with PD experienceing Freezing of Gait as diagnosed by a movement disorders specialist were selected from the University Hospital Clinic. Freezing occurred in six patients (1 with STN-DBS), over two laboratory visits. All study subjects provided informed consent and were de-identified. This study was approved by Western University's Research Ethics Boards (REB).

B. Apparatus

Foot pressure changes during ambulation were captured using the F-Scan® system (TekScan, Inc.) at a sampling rate of 50 frames per second. The sensor system was a pair of wearable foot insoles with a maximum number of 60 force sensors in the Anterior-Posterior direction and 21 sensors in the Medial-Lateral direction. To accommodate for different shoe sizes, the insoles were cut according to the patterns provided. All freezing episodes were captured from the waist down with a video camera.

C. Clinical Scales and Fall History

UPDRS III (items 18-31) and FOG-Q were administered by a movement disorders specialist for total motor score and freezing, respectively. Mood assessments were captured using the BECK anxiety scale as well as the BECK depression inventory. Fall history was taken from patients' medical records from the clinic.

Figure 1. Experiment setup; patient with calf unit and sensor connectors (left). A sample of shoe insert sensor matrix containing 60 rows and 21 columns of pressure sensors (right)

*This research was supported in part by TEVA Canada Ltd.

F. Rahimi, Si Yu Xian, and M. Delrobaei are with at the National Parkinson Foundation Centre of Excellence, Lawson Health Research Institute, London, ON, Canada (Phone: 519-685-8500Email: frahimi@uwo.ca,). M. Jog is the Director of the NPF Centre of Excellence, with Lawson Health Research Institute and Professor, in the Department of Clinical Neuroscience, Western University, London, ON, Canada (mandar.jog@lhsc.on.ca).

D. *Gait Tasks*

Patients performed five gait tasks designed to elicit freezing in the laboratory. In each visit, after calibrating the sensors to patient's weight, they began with a standard 3-m timed-up-and-go (TUG), which includes one 180-degree turn, followed by four modified versions of the same task:

2. 3m TUG while performing a parallel cognitive load of counting backward at three levels of difficulty
3. 3-point TUG in which 180-degree is replaced by a 90-degree turn. In this task, the left or right turn is known to the patient before the beginning of task
4. 3-point TUG with surprise 90-degree unplanned turns
5. 3m TUG replaced with 360-degree turns

Patients performed three trials for each task and were given rests between tasks to reduce fatigue. Trained researchers were alongside patients to prevent falls.

E. *Analysis*

This study focused on only those freezing episodes that happened during straight walking. Synchronization between video and foot pressure data was performed using an identifiable mechanical tapping routine on the right ankle accelerometer sensor in both pressure data and video. Episodes were identified in kinematic data through video synchronized time and duration of each episode was recorded. Three second standing episodes were also identified in instances where patients were not performing the above tasks for comparison against freezing episodes. The range of center of pressure (CoP) during walking was extracted using the reliable maxima of CoP in both Anterior-Posterior (AP) and Medial-Lateral (ML) directions (Fig.2). The average CoP position for standing and freezing episodes were plotted onto a sensor activation pattern of the patients' feet (Fig.2).

Raw sensor data exported from the F-Scan system was used to produce a sensor activation pattern of the foot. Each frame of data provided the pattern of sensors activated.

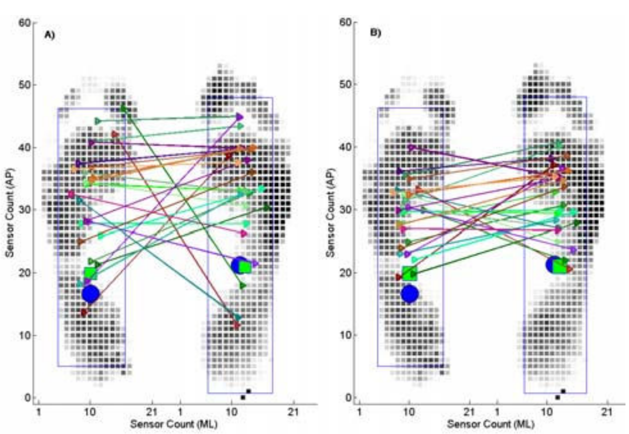

Figure 2. Activation pattern of foot sensors for patient 02. The large circle and square represent average CoP for standing and walking, respectively. Average CoP positions for freezing episodes are represented by triangle and lines connect the CoP positions of the same episode. A) CoP positions for the 1st second of all episodes.B) CoP positions for the entire duration of all episodes.

Activation patterns of walking were produced by summating all frames within task 1 to produce a frequency pattern that is represented in greyscale gradient, in which frequently activated sensors are darker.

When the foot is lifted during walking, the F-Scan system returns a null value for center of pressure and these null values were ignored. Freezing and standing instances were not affected since no complete lifting of the feet occurred. Average CoP positions for the first second and full duration of freezing episodes were used for analysis.

F. *Statistical Analysis*

Statistical analysis was performed using the independent t-test by variable for all comparisons. We compared mean durations of freezing episodes between patients. Next, Average CoP values during freezing were compared to average CoP values during standing and walking. Lastly, absolute difference between mean left and right CoP during freezing were compared against zero for statistical significance. Significance was tested at an alpha level of 0.05 throughout the study and only *p*-values <0.01 were reported. Boxplots were used to graphically represent distribution of durations (Fig. 3) and mean CoP values (Fig. 4).

III. Results

A. *Patient Demographics*

Demographic data for all the 18 participants and the 6 patients with freezing episodes are presented in Table I. All patients in the study have clinical freezing of gait, but only 6 patients have exhibited significant freezing in the laboratory. Demographics for patients who froze in the lab were not significantly different than the full patient group (results not shown). Fall history within 12 months of the study showed that 4 patients (02, 05, 15, and 19) were frequent fallers. One patient (06) did not have recorded falls within the 12 months and one patient (20) experienced some falls within the last 12 months.

B. *Freezing severity*

Summary of freezing severity for patients who exhibited FoG in the laboratory is presented in Fig. 3. Severity of FoG can be captured by duration and count/frequency of freezing episodes. Duration of episodes per patient is represented in Fig 3A. Patients 1, 3, and 4 had significantly different durations than patients 5 and 6. Durations of freezing for patient 2 was only significantly different than patient 6. Patient 5 had a significantly different freezing duration than patients 1, 3, 4, and 6. Lastly, Patient 6 had significantly different durations than all patients. Episodes of freezing only during straight walking were used for analysis. Patients 2, 5, 6, 15, 19, and 20 experienced 26, 7, 9, 12, 10, and 73 episodes, respectively (Fig 3B).

C. *Observable Freezing Characteristics*

Mean CoP for freezing episodes, mean standing CoP as well as mean walking CoP were plotted on to the activation pattern of each patient's feet, as shown in Fig. 2. Lines connected the CoP positions of the two feet during freezing. Consistent across all patients, the freezing CoP positions averaged over the first second were more scattered when compared to the entire duration of the freeze. This is evident by the decreased slopes in the lines that connect the freezing episodes.

D. CoP Positions –AP axis

Center of Pressure position comparisons are summarized in Table II. Mean CoP positions of each foot during standing were compared to mean CoP of freezing episodes of each individual patient. For patients 02, 05, 15 and 19, all mean CoP positions during freezing were in front of mean standing and walking CoPs.

TABLE I. PARTICIPANTS' DEMOGRAPHICS AND CLINICAL PRESENTATION / SCALES

Patient	***02***	***05***	***06***	***15***	***19***	***20***	***6 With FoG***	***All 18***
Age (Yrs)	66	59	73	65	70	79	69±7	71±7
Disease Duration (Yrs)	10	3	4	6	5	3	10±4	12±4
Years with FoG	12	8	5	15	8	>3	5±3	5±2
UPDRS III	18	11	22	13	14	33	19±8	18±7
BAI	4	27	18	20	28	24	16±10	17±9
BDI	16	6	10	1	14	15	10±6	10±7
FOGQ	23	15	16	13	14	20	17±4	16±3
# of FoG Episodes	26	12	7	73	9	10	137	137
Fall History	C[a]	C	A	C	C	B	N/A	N/A

a. A- No falls. B- Some falls. C- Frequent falls.

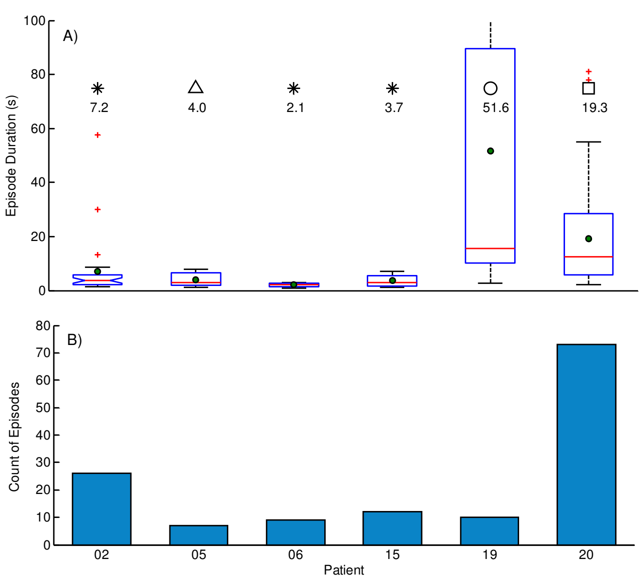

Figure 3. Count and duration of freezing episodes for patients with FoG. A) Boxplots of durations of FoG episodes. Red lines represent median freezing durations. Green dots represent mean freezing durations. Values reported on figure are mean values. □- significantly different (S.F., $p < .05$) than patients 1-5; O- S.F. than patients 1,3,4,6; Δ- S.F. than patients 5-6; *- S.F. than patient 6. B) Bar-graphs of total counts of freezing per patient.

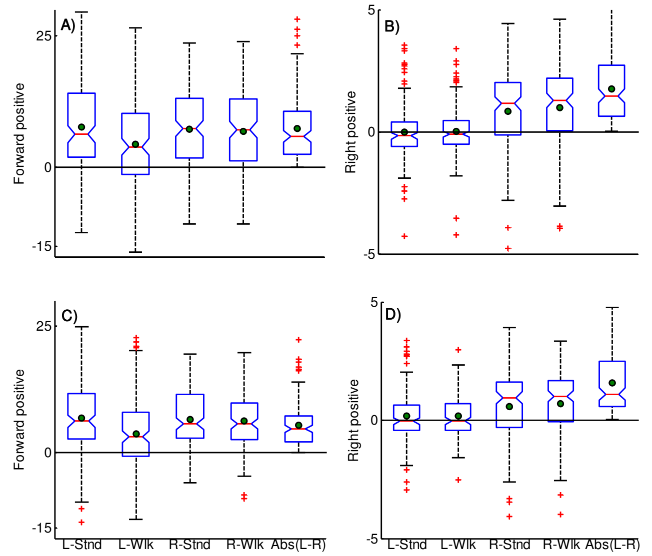

Figure 4. Boxplots of mean CoP comparisons for freezing group. L/R-stnd represents mean freezing CoP against standing for left and right feet, respectively. L/R-Wlk represents mean freezing CoP against walking. Abs(L-R) represents absolute difference between left and right CoP position for all freezing episodes. A) Mean CoP comparisons for the 1st second of freezing in the AP direction. B) Mean CoP comparisons for the 1st second of freezing in the ML direction. C) Mean CoP comparisons for the entire duration of freezing in the AP direction. D) Mean CoP comparisons for the entire duration of freezing in the ML direction.

All CoP positions were significantly different than standing and walking CoP, except in left foot comparison for patient 15. In group analysis of all six patients, average difference between CoP of freezing and standing was significantly different than zero ($p<0.01$) for both feet (Table II). Patients 06 and 20 did not have significantly different freezing CoP when compared to standing and walking on the left foot. Freezing CoP for the right foot in patient 06 was significantly behind both standing and walking CoP. In Patient 20, freezing CoP for the right foot was significantly in front of both standing and walking CoP.

The absolute difference in CoP between the left and right foot during freezing was also analyzed for statistical significance. The difference between left and right foot in all patients were not significantly different than zero (results not shown), indicating that either foot could have a freezing CoP in front of the other. However, the absolute difference was significantly different ($p<0.01$) than zero (Fig.3, Table II)

E. CoP Positions – ML axis

Unlike in the AP direction, there is no consistent trend among the patients in the ML axis. In group analysis of all six patients, average freezing CoP positions were significantly to the right when compared to standing and walking in the right foot ($p<0.01$). Freezing CoP positions in the left foot were to the left of both standing and walking CoP, but these differences were not statistically significant.

TABLE II. SUMMARY OF FREEZING OF GAIT COP COMPARISONS

Anterior-Posterior Axis							
Patient	***2***	***5***	***6***	***15***	***19***	***20***	***Group***
Left vs. Standing	F*[a]	F*	F	F*	F*	B	F*
Left vs. Walking	F*	F*	B	F	F*	F	F*
Right vs. Standing	F*	F*	B	F*	F*	F*	F*
Right vs. Walking	F*	F*	B*	F*	F*	F*	F*
|L-R|	RF*	RF*	LF*	RF*	LF*	LF*	LF*
Medial-Lateral Axis							
Patient	***2***	***5***	***6***	***15***	***19***	***20***	***Group***
Left vs. Standing	R*	R	L*	L	R*	L	L
Left vs. Walking	R*	R	R	L	R	R	L
Right vs. Standing	L*	R*	R	R*	R	L	R*
Right vs. Walking	L*	R	L	R*	L	R	R*

a. F- Freezing CoP in front of standing or walking. B-FoG CoP behind standing or walking. RF-Right foot CoP position in front of left foot. LF-Left foot CoP position in front of right. R-Freezing CoP to the right of standing CoP. L-Freezing CoP to the left of standing CoP. *- P<0.01

IV. CONCLUSION

We have presented a new way to analyze and kinematically capture freezing of gait in this study. We observed a tendency that in the 1st second of freezing, the CoP positions appeared to be more scattered relative to each other. Freezing CoP tends to become more tightly clustered when the entire duration is analyzed. This finding could represent the spontaneity of freezing, leading to abrupt stops. When freezing lasts beyond one second, freezers tend to “gather” themselves towards a freezing equilibrium that is still different than that of standing CoP.

All patients in this study exhibited different characteristics in severity, as shown in our results of freezing duration and count. Despite this, there is a consistent pattern in the AP direction of mean freezing CoP. Patients suffering from freezing of gait tend to have their center of pressure shifted forward. This could indicate their continued intention to walk, but it could also increase their risk of falling, if the shift forward is such that the center of gravity is ahead of their center of pressure[8]. This idea is consistent with previous findings that Parkinson’s patients who experience recurrent falls have increased anterior-posterior sway [9]. Fall history of the four patients who exhibit the front shifting of CoP show a pattern of frequent falls, up to several falls a day. This represents a clear risk of a forward shift in CoP during freezing. In the medial-lateral axis, there was no clear trend demonstrated that could be related to falls. However, the uniqueness of this parameter among patients suggests that there are personal characteristics in freezing. Since previous bio-mechanic studies show that medial-lateral CoP is important for step generation and it is impaired in patients with freezing of gait [10], unique characteristics in this axis could represent attempts to restart gait after freezing. These are interesting possibilities and should be further investigated. The fact that absolute difference between the CoP between the feet is significantly greater than zero may reveal that feet movements in both AP and ML directions during the freeze are completely out of phase.

Tan et al. have shown that FoG in Parkinson’s patients have proprioceptive deficits found only in Parkinson patients with FOG. These findings suggest that the risk of falling may be increased because of their lack of proprioceptive feedback during freezing required to make the appropriate postural adjustments to prevent falling [11]. There were two patients (06 and 20) who did not follow this pattern of forward shifting of CoP. Interestingly, these patients also experienced less falls than other freezers in the study. This could represent a balance strategy used by these patients to prevent falling. Future studies should investigate the effectiveness of this technique in fall prevention. Patients can be taught to shift their weight to the heel of one foot to create a more stable stance during freezing in a safe rehabilitation setting. As well, investigation of the last portion of freezing episodes before patients resume gait could shed light on or reveal strategies for freeze breaking.

ACKNOWLEDGMENT

We acknowledge the contribution of the patients and staff at the Movement Disorders Centre, London Health Sciences Centre, London, Ontario, Canada. Special thanks to Ms. Angie South, Ms. Danielle Bell Boucher, Ms. Lynn Zhu and Dr. Yahia Mohammed for assisting in data collection.

REFERENCES

[1] J. G. Nutt*, et al.*, "Freezing of gait: moving forward on a mysterious clinical phenomenon," *Lancet Neurol,* vol. 10, pp. 734-44, Aug 2011.

[2] A. Contreras and F. Grandas, "Risk factors for freezing of gait in Parkinson's disease," *J Neurol Sci,* vol. 320, pp. 66-71, Sep 15 2012.

[3] N. E. Allen*, et al.*, "Recurrent falls in Parkinson's disease: a systematic review," *Parkinsons Dis,* vol. 2013, p. 906274, 2013.

[4] M. E. Morris*, et al.*, "Gait festination and freezing in Parkinson's disease: pathogenesis and rehabilitation," *Mov Disord,* vol. 23 Suppl 2, pp. S451-60, 2008.

[5] A. Nieuwboer*, et al.*, "Cueing training in the home improves gait-related mobility in Parkinson's disease: the RESCUE trial," *J Neurol Neurosurg Psychiatry,* vol. 78, pp. 134-40, Feb 2007.

[6] C. Moreau*, et al.*, "[Gait disorders in Parkinson's disease: and pathophysiological approaches]," *Rev Neurol (Paris),* vol. 166, pp. 158-67, Feb 2010.

[7] E. E. Tripoliti*, et al.*, "Automatic detection of freezing of gait events in patients with Parkinson's disease," *Comput Methods Programs Biomed,* vol. 110, pp. 12-26, Apr 2013.

[8] F. B. Horak*, et al.*, "Direction-specific postural instability in subjects with Parkinson's disease," *Exp Neurol,* vol. 193, pp. 504-21, Jun 2005.

[9] G. K. Kerr*, et al.*, "Predictors of future falls in Parkinson disease," *Neurology,* vol. 75, pp. 116-24, Jul 13 2010.

[10] Y. Okada*, et al.*, "Abnormalities of the first three steps of gait initiation in patients with Parkinson's disease with freezing of gait," *Parkinsons Dis,* vol. 2011, p. 202937, 2011.

[11] T. Tan*, et al.*, "Proprioceptive deficits in Parkinson's disease patients with freezing of gait," *Neuroscience,* vol. 192, pp. 746-52, Sep 29 2011.