**Effects of aging and Parkinson's disease on joint coupling, symmetry, complexity and
variability of lower limb movements during gait**

Kiwon Park^{1,2}, Ryan Roemmich³, Jonathan Elrod³, Christopher J. Hass³, Elizabeth T. Hsiao-Weckslers¹

¹Department of Mechanical and Science Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA;

²Department of Mechanical and Aerospace Engineering, Trine University, Angola, IN 46703, USA;

³Department of Applied Physiology and Kinesiology, University of Florida, Gainesville, FL 32611, USA;

Address correspondence to:

Elizabeth T. Hsiao-Weckslers, Ph.D.
Professor, Willett Scholar, and Associate Head of Undergraduate Programs
Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign, MC-244
1206 W. Green Street
Urbana, IL 61801
USA

Telephone: 217.333.3415
Fax: 217.244.6537
Email: ethw@illinois.edu.

Word count total 3800 (main text), Abstract (Limit 250 words) – 244
Number of Tables: 3, **Number of Figures:** 1

1 **ABSTRACT**

2
3 *Background:* Natural aging and disease processes such as Parkinson's disease often lead to gait
4 impairment. This impairment often manifests as changes in symmetry, complexity, and
5 variability of lower limb joint movements during gait as compared to young healthy adults.
6 Current gait assessment tools primarily focus on discrete events during gait or are based on
7 univariate statistical techniques. Therefore, they fall short in examining spatiotemporally
8 complex gait characteristics including interactions across multiple segments and joints.

9
10 *Methods:* Treadmill walking data from ten healthy older adults and ten individuals with
11 idiopathic Parkinson's disease were collected at their self-selected speed. Additionally treadmill
12 walking data from previously collected gait studies on 20 young adults were also used. This
13 study utilized new gait assessment techniques that quantitatively examined joint coupling
14 characteristics (via Condition Signature Analysis), variability and complexity of joint variables
15 (via Phase Portrait Analysis), and movement asymmetry (via Regions of Deviation Analysis) of
16 the three different groups.

17
18 *Findings:* People with Parkinson's disease had the highest asymmetry among the three groups.
19 Aging and Parkinson's disease significantly decreased complexity of hip and ankle joint
20 movements, respectively, while there were no significant differences in variability measures
21 among the three groups. The Condition Signature Analysis method suggested significant
22 differences of joint coupling patterns due to aging and Parkinson's disease.

1 *Interpretation:* These new gait assessment techniques successfully captured changes in
2 asymmetry, variability, complexity, and joint coupling patterns. Quantitative gait assessment
3 using these tools can **be used to detect** various types of gait impairments.

4

5 **Keywords:** Parkinson's disease, Gait, Aging, Gait assessment

1. Introduction

Gait disturbances and instability due to aging and Parkinson's disease (PD) may lead to injuries, hip fractures, fear of falling, and restriction of activities which in turn result in loss of independence and mortality (Ashburn et al., 2001, Johnell et al., 1992). With the advent of computerized motion capture technology, there have been various methods to assess pathological gait patterns. Current tools, however, primarily examine discrete events or are based on univariate statistical techniques; thus falling short in quantifying spatiotemporally complex motion patterns and in detecting interactions across multiple segments and joints (Diop et al., 2004, Knoll et al., 2004, Hausdorff, 2004a, Devita et al., 1997). New methods for examining joint variability, symmetry, and coupling in spatiotemporally complex gait movement patterns may provide added insight to this association.

Variability and complexity of gait have been quantified using a number of different metrics. Variability of joint motion patterns during gait has been shown to be predictive of future falls (Schaafsma et al., 2003). Previous studies reported that increased stride-to-stride variability of traditional gait measures, such as stride length, stride time, and swing time, was observed in the elderly and was associated with future falls in prospective studies (Hausdorff et al., 2001). Furthermore, the increased variability of movement exhibited by people with PD may be related to a decline in motor control and dynamic balance, which heighten fall risk (Sheridan et al., 1987, Blin et al., 1990). In gait analysis, complexity has been evaluated by a variety of different techniques. However, conflicting reports are numerous due to differences in the metrics used. For example, Goldberger et al. found decreased gait complexity in stride timing due to disease and aging using fractal analysis (Goldberger et al., 2002), while another demonstrated increased

1 complexity using Hurst exponents (Munoz-Diosdado et al., 2003). DiBerardino et al. proposed a
2 method to quantify the complexity and inter-cycle variability of phase portrait shapes of lower
3 limb motions during multiple continuous gait cycles (DiBerardino et al., 2010). Phase portraits
4 enable us to characterize multiple continuous gait cycles of individual body segments, while
5 other complexity studies frequently use the resultant stride or step timing patterns. Thus,
6 quantitative assessment from this method provides insight into intra-cycle fluctuation or
7 smoothness (complexity) and inter-cycle fluctuation (variability) of phase portrait shapes.

8 Asymmetry in lower extremity movement observed in people with PD and older adults
9 has also been associated with gait instability and fall risk in these populations (Bautmans et al.,
10 2011, Lewek et al., 2010). However, the majority of studies investigating gait asymmetries rely
11 on patient report, qualitative interpretation such as visual inspection, or on discrete
12 spatiotemporal measures (Knoll et al., 2004, Hausdorff, 2004b, Diop et al., 2004, Danion et al.,
13 2003, Schwartz et al., 2008, Owings and Grabiner, 2004). Continuous techniques such as
14 Regions of Deviation analysis allow investigation of complex movements which span multiple
15 joints across the entire gait cycle (Shorter et al., 2008, DiBerardino et al., 2012).

16 Joint coupling patterns and the coordination of motion during gait may also be associated
17 with gait impairment in people with PD and the elderly. Since human gait is a complex motion
18 involving interaction between multiple body segments, in the course of walking or running gait
19 impairment such as improper joint coupling and coordination may be critical to sustained gait. It
20 has been shown that asynchrony of joint coupling characteristics is associated with
21 musculoskeletal injuries (DeLeo et al., 2004, Tiberio, 1987, Hamill et al., 1999). Timing
22 discrepancies among lower limb joint motions may lead to excessive stress at the knee joint

(Hamill et al., 1999). Thus, each joint in the lower extremity should move synchronously; and asynchrony in these motions due to either internal or external perturbation may result in impaired gait (DeLeo et al., 2004). Previous methods, however, have focused on single coupling pairings (of either joints or body segments), and thereby fail to capture the effects of one joint on multiple joints, i.e., multi-joint coupling patterns. In contrast with these past studies, the Condition Signature Analysis seeks to characterize joint couplings throughout the entire locomotive apparatus using a single representative diagram (Park et al., 2012) .

The purpose of the current study was to investigate possible changes in coupling patterns, symmetry, complexity and variability of lower extremity joints to characterize older adult and Parkinsonian gait behaviors. Recently developed gait assessment tools developed by Shorter et al. (2008), DiBerardino et al. (2010), and Park et al. (2012) were applied to gait data collected on healthy older adults, older adults with Parkinson's disease, and healthy young adult control subjects.

2. Methods

2.1. Participants

Ten healthy older adults (OA) and ten individuals with idiopathic PD (UPDRS motor score 24 (SD 7)) were recruited for the study (OA: mean age 59 (SD: 9) years, PD: mean age 64 (SD: 9) years). There was no significant difference in the age of the OA and PD groups. For persons with PD, participants were excluded from the study if they had a history of stroke, exposure to toxins or neuroleptics, history of encephalitis, and neurological signs of upper motion neuron disease, supranuclear gaze palsy, or significant orthostatic hypotension. The protocol was approved by

the institutional review boards at the University of Florida and the University of Illinois, and informed consent was received for each participant. Experimental data were collected in the Department of Applied Physiology and Kinesiology at the University of Florida. Additionally data from previously collected gait studies on 20 young adult (YA) male subjects (mean age 23 (SD: 2) years) (DiBerardino et al., 2010) were also used in this study.

2.2. Experimental Procedure

For PD and OA subjects, treadmill walking data were collected during a single test session. Participants walked for five minutes at their self-selected speed on an instrumented split-belt treadmill (Bertec Corporation, Columbus, OH). Self-selected speed was determined while walking without needing additional support. PD subjects participated in the experiment under off-medication condition. **There was no significant difference in the self-selected older adult (1.1 (SD 0.1) m/s) and PD (0.9 (SD 0.3) m/s) speeds.** For YA subjects, treadmill walking data were collected during a three minute self-selected speed gait trial. Data collection procedures for the YA group were summarized previously (DiBerardino et al., 2010).

For the PD and OA subjects, kinematic data were collected at 120 Hz using a 10-camera motion capture system (Vicon, Lake Forest, CA). Thirty-five retro-reflective markers were placed over anatomical bony landmarks according to the Vicon's Plug-in-Gait marker system. These kinematic marker data were converted into lower limb joint angle measurements using Vicon Nexus. Gait events were manually labeled based on marker velocity profiles, with the timing between consecutive heel strikes for a given leg defining a single gait cycle. After allowing for 25 gait cycles of accommodation to the treadmill, ankle, knee, and hip

flexion/extension angular displacements and velocities were calculated over the next 20 consecutive gait cycles during each walking trial. A custom-written MATLAB program was used to perform all calculations (R2010a, The MathWorks, Natick, MA). For YA subjects, kinematic data were captured at 120 Hz using a six-camera motion capture system (Vicon 460 Datastation; Oxford, UK). Joint variables were computed from surface markers located over the sacrum, bilateral anterior superior iliac spine, mid-thigh, femoral lateral epicondyle, tibial tuberosity, lateral malleolus, 1st and 5th metatarsal heads, and heel. Custom Matlab codes were used to perform all calculations (R2008a, The MathWorks; Natick, MA, USA). Kinematic joint variables during gait were aligned by linearly compressing or expanding the time axis to make each gait cycle in percentages (0-100%), and all of these studies used the same gait cycle definition (i.e., the timing between consecutive heel strikes) separately for each limb.

2.3. Gait Assessment techniques

Gait kinematics were examined to assess the effects of aging and PD on asymmetry, variability, complexity, and joint coupling patterns using three assessment methods: Regions of Deviation analysis (Shorter et al., 2008), variability and complexity of phase portraits (DiBerardino et al., 2010), and Condition Signature Analysis (Park et al., 2012).

2.3.1. Regions of Deviation analysis

Regions of Deviation (ROD) analysis identifies regions of the gait cycle where joint angular displacements deviated from normative behavior (Shorter et al., 2008). This analysis technique is used to evaluate deviations in symmetry between bilateral joints or deviation of an individual

joint's motion relative to healthy normative behavior. Thus ROD analysis consists of two assessments: Symmetry Regions of Deviation (SROD) and Individual Regions of Deviation (IROD). Both assessments quantify deviations in the given data that lay one standard deviation outside of the normative group mean. Data are analyzed at each point in the gait cycle after the time series data have been normalized to 100% gait cycle with 1% increments. Healthy normative gait patterns for the ROD analysis were based on the gait data from the YA group.

SROD analysis determines the magnitude and timing of when bilateral joint angle pairs demonstrate asymmetric behavior across the gait cycle. To perform SROD analysis, first the bilateral angular difference of the YA group (normative gait patterns, N) between the left and right sides (e.g., left hip - right hip ($\Delta\theta_{Hip}^N$), left knee - right knee ($\Delta\theta_{Knee}^N$), etc.) was computed for each gait cycle, and then averaged over the 20 consecutive cycles. A negative value indicates a smaller value for the left side. For a given joint of a particular subject from three testing groups (YA, OA, and PD), the deviation from healthy normative behavior of the bilateral angular difference between the left and right sides (i.e., $\Delta\theta_{Hip}^{OA} - (\Delta\theta_{Hip}^N \pm S.D.^N_{Hip})$, $\Delta\theta_{Knee}^{OA} - (\Delta\theta_{Knee}^N \pm S.D.^N_{Knee})$, where $\Delta\theta_{Hip}^{OA}$ is subject-specific averaged angular difference of each testing group, $\Delta\theta_{Hip}^N$ is averaged angular difference of all normative test subjects, and $S.D.^N_{Hip}$ is standard deviation of all normative test subjects) was computed and expressed as the “SROD value” for each data point in a gait cycle. Average SROD values for each bilateral joint pair were determined over the 20 consecutive cycles.

Similarly, IROD analysis identifies the magnitude and timing of motion of a specific or individual joint (e.g., left hip, right ankle) when deviating from expected healthy normative behaviors. To perform IROD analysis, first each individual joint angle ($\theta_{Left Hip}^N$, $\theta_{Left Knee}^N$,

$\theta_{Right\ Hip}^N$, etc.) of the YA group (normative gait patterns, N) was identified and averaged over the 20 consecutive cycles. For a given joint of a particular subject from three testing groups (YA, OA, and PD), the deviation from healthy normative behavior (i.e., $\theta_{Right\ Hip}^{OA} - (\theta_{Right\ Hip}^N \pm S.D.^N_{Right\ Hip})$, $\theta_{Right\ Knee}^{OA} - (\theta_{Right\ Knee}^N \pm S.D.^N_{Right\ Knee})$, where $\theta_{Right\ Hip}^{OA}$ is subject-specific averaged joint angle of each testing group, $\theta_{Right\ Hip}^N$ is averaged joint angle of all normative test subjects, and $S.D.^N_{Right\ Hip}$ is standard deviation of all normative test subjects) was computed and expressed as the “IROD value” for each data point in a gait cycle.

SROD and IROD values were computed for the three test groups (YA, OA, and PD) and for each lower limb joint (ankle, knee, and hip). For each SROD or IROD data set, three parameters were determined: *peak value* (magnitude of peak deviation), *peak timing* (timing of peak deviation), and *total ROD value* (integral of the absolute value over the full gait cycle). Total ROD value provides insight into the total magnitude of ROD values throughout the full gait cycle. While peak ROD value indicates a maximal deviation in the gait cycle, total ROD value provides important insight into how subjects modulate their joint movements to minimize ROD values throughout the full gait cycle.

2.3.2. Variability and Complexity

Planar phase portraits, which represent changes in joint angular position versus velocity over each gait cycle, are approximately elliptical shapes. Metrics to quantify the variability and complexity of phase portrait shapes over multiple gait cycles have been described previously (DiBerardino et al., 2010).

Inter-cycle variability has been assessed by quantifying fluctuations of the phase portrait

centroid over multiple gait cycles. The centroid was defined as the mean value of all (x=angular position, y=angular velocity) data points in the phase portrait for each gait cycle. Specifically, variability has been characterized by computing the total Cartesian distance that the centroid traveled on the phase plane (*centroid drift*) and 95% confidence elliptical area (*centroid swept area*) generated by the excursion of the centroid over multiple cycles.

The complexity of the motion pattern has been assessed by the frequency content of the phase portraits (*# harmonics*). Using Fourier-based methods, the structure or complexity was quantified by the number of harmonic frequencies suitable for fitting a phase portrait shape. More specifically, this number is based on the minimum number of harmonics in a reduced-order fit, that is capable of reproducing 99.9% of the phase portrait shape over the 20 gait cycles. Phase portraits with a larger number of harmonics indicate greater complexity of motion patterns that require more harmonics to characterize shapes.

2.3.3. Condition signatures

Condition Signature Analysis (CSA) (Park et al., 2012) was used to examine coupling between twelve joint movements (bilateral ankle, knee and hip angular displacements and velocities) over 20 gait cycles. Although most of previous studies have focused on single coupling between bilateral body segments (e.g. left knee vs. right knee), CSA examines the coupling across multiple, not necessarily bilateral or neighboring, segments and joints to characterize spatiotemporally complex gait patterns. Ipsilateral and contralateral joint parameter pairs were examined to identify coupling and coordination patterns between aging or PD and young healthy normative behavior (YA vs. OA, PD vs. OA). Temporal cross-correlation compared the shape

and timing of these time-series gait parameters. From these cross-correlations, the maximum cross-correlation and associated critical phase shift values were recorded. Two condition signature diagrams were created that highlighted significant differences due to aging and PD (using unpaired t-tests with $\alpha=0.05$) among maximal cross-correlation or critical phase shift values for each joint pairing. In the condition signature diagram, black colored cells of joint variable pairs suggest that there were significant differences in shape (maximal cross-correlation: lower left triangle of array) or timing (critical phase shift: upper right triangle of array) of corresponding joint couplings between two conditions.

2.4. Statistical analyses

In addition to the Condition Signature Analysis, statistical analyses were performed to assess the effect of aging and PD on joint asymmetry, variability, and complexity (SPSS Inc., Chicago, IL; v15). ANOVA tests were performed for the three groups to test for differences in asymmetry measures (SROD, IROD), variability measures (centroid swept area, centroid drift), and complexity (# harmonics). Tukey HSD analysis was used for post-hoc comparisons. All tests were conducted using a significance level of $\alpha=0.05$.

3. Results

The ANOVA tests found significant differences among the three groups for asymmetry (SROD, IROD) and complexity metrics (Tables 1-3). Post-hoc tests revealed that aging and PD significantly increased lower limb joint asymmetry. Total SROD values of hip, knee, and ankle joint for the PD group were significantly larger than the other two healthy groups (YA, OA)

(Table 1). Aging increased total IROD values for all three lower extremity joints (hip, knee, and ankle), while PD did not significantly affect IROD metrics (Table 2). Aging decreased the complexity of left hip joint movement and PD decreased the complexity of left and right ankle joint movements (Table 3). A variability measure, centroid area, showed a non-statistically significant trend that the PD group had more variable joint movement patterns for the right knee ($p=0.08$) than the other healthy groups (Table 3). The condition signature also indicated changes in joint coupling patterns between different groups, such as bilateral joint asymmetry, neighboring joint coupling, and level of disturbed gait (YA vs. OA, PD vs. OA) (Fig.1).

4. Discussion

The effects of aging and PD on symmetry, complexity, variability, and joint coupling patterns were investigated to better understand older adult and Parkinsonian gait behavior. The results from this study suggest that people with PD exhibited the highest asymmetry among the three groups (Table 1). Individual lower extremity joint motions for young adults were significantly different from the other two groups (OA, PD), but there was no significant difference between older adults and people with PD (Table 2). Although no significant differences were found for any variability measures (centroid area, centroid drift) among the three groups, there was a trend that centroid area of the PD group was greater than the other two healthy groups (Table 3). While young adults had the most complex hip joint movements among the three groups, people with PD had the least complex ankle joint movements (Table 3).

Results from our SROD analysis demonstrate significant asymmetry in all three lower extremity joints in persons with PD relative to healthy adults (Table 1). These findings are

consistent with previous studies which suggest that PD patients exhibited increased bilateral asymmetry in lower extremity muscle activation timing, timing of swing duration, and arm swing trajectories (Yogev et al., 2007, Miller et al., 1996, Lewek et al., 2010). PD usually presents as an asymmetric neurological process and results in motor asymmetry (Uitti et al., 2005, Yust-Katz et al., 2008). Cardinal symptoms such as tremor, rigidity, and bradykinesia might lead to gait asymmetry in joint movements, and thus it is possible that joint asymmetry during gait may be utilized as another diagnostic or disease progression tracking tool for PD after conducting longitudinal study with larger population groups. In the present study, SROD analysis provides quantitative assessments for the asymmetrical aspect of PD by highlighting the magnitude and timing of asymmetry. While there was no significant difference in the peak magnitude and timing of asymmetry due to PD, people with PD had greater total SROD values than the other healthy adults. These results indicate that there are inconsistent gait asymmetry patterns among people with PD as they had different peak magnitudes and timings of bilateral asymmetry. However, the PD group showed significantly greater total bilateral gait asymmetry (i.e. integral of absolute deviation of bilateral angular difference) than the other healthy adults (YA and OA). Bilateral gait asymmetry may generate dynamic imbalance, which in turn can result in increased fall risk. This argument can be supported in that increased asymmetry has been observed in both people with PD and fall-prone individuals (Yogev et al., 2007).

IROD analysis identified the effect of aging on individual lower limb joint movement. For bilateral hip, knee, and ankle joints, total IROD values of the young adults group were significantly smaller than older adults and people with PD (Table 2). However, PD had no effect on IROD measures for all of lower extremity joints. These results suggest that aging increased

1 deviation in joint motion, and metrics for individual joints might not capture the effect of PD on
2 gait behavior.

3 Aging and PD significantly decreased complexity of hip and ankle joint movements,
4 respectively (Table 3). Greater complexity in the phase portrait of the hip joint for young adults
5 **was indicated by** an increased number of harmonics to describe their hip joint motion shapes.
6 Conversely, this result can be interpreted as an increased smoothness of phase portrait structure
7 in lower limb joint motions of the older adults and people with PD. Complexity relies on signal
8 fluctuation frequency and irregularity. The results from the complexity analysis suggest that
9 human gait loses complexity of joint motions with aging or disease such as PD. These results are
10 consistent with previous studies that aging is associated with a loss of complexity in
11 physiological system dynamics (Lipsitz and Goldberger, 1992, Lipsitz, 2002). It is possible that
12 older adults might use a more cautious strategy to minimize complexity of hip joint motions and
13 PD patients might focus on ankle joint movements rather than hip and knee joint during walking
14 in order to compensate for their decreased gait instability.

15 In contrast with the results of complexity measures, there was no significant difference
16 of variability measures among the three groups. Recognizing that variability relates to deviation
17 from the mean value, these results suggest that aging or PD generate more complex gait behavior,
18 but might not change deviation of joint motion from the mean value. Therefore, metrics which
19 measure only deviation of joint movements from the mean values might be unable to detect the
20 effect of aging or PD.

21 The Condition Signature Analysis identified changes in joint coupling patterns due to
22 aging and PD (Fig. 1). The temporal cross-correlation function between two bilateral joint

variables (i.e., left vs. right knee joint displacement, left vs. right ankle joint displacement) quantified bilateral symmetry of timing and shape of two joint motions. In the condition signature diagram, black colored cells of bilateral joint variable pairs suggest that there were significant differences in shape (maximal cross-correlation) or timing (critical phase shift) of corresponding bilateral joint couplings between two conditions indicating asymmetrical gait behavior. The other joint variable pairings in the condition signature (e.g. LK vs. RH, LH vs. LA, LK vs. RA, etc.) are associated with the magnitude of perturbed gait behavior. During continuous walking, each body segment and joint move simultaneously and are coordinated by the central nervous system to maintain sustained gait (Duysens and Van de Crommert, 1998). Assuming that normative gait has minimal disturbance throughout multiple lower limb motions, abnormal joint coupling patterns (deviations in joint coupling patterns from the normative data) can be considered as a perturbation. In the condition signature, black colored cells, not associated with bilateral or neighboring joint couplings, can be used to gain insight into the magnitude of perturbation during gait such as the joint couplings between right knee and left ankle. Each black colored cell indicates significant difference of the corresponding joint coupling between test groups, and more black colored cells suggest that these joint couplings are disturbed during gait. Increased level of disturbance may lead to increased gait instability. Finally, these detailed joint coupling patterns characterize a specific gait behavior, and were used to examine various gait patterns from the **older adults** and people with PD.

For the comparison of older adults with young adults, all joint angular displacements and velocities except knee joint angle had significantly different maximal cross-correlation values between left and right joint variables ($p < 0.05$). On the other hand, another symmetry measure,

SROD analysis used in this study indicated that only older adults' knee joint angle significantly deviated from joint motions of young adults, but not hip and ankle joint angles. This discrepancy of the results is due to different aspects of each analysis. Temporal cross-correlation is a measure of the similarity in overall shape between two time-series, while SROD computes angular difference between left and right side joint variables. Thus, these results suggest that shapes of bilateral joint variables were significantly different for most of lower limb joints, but changes in the magnitude of bilateral joint angle pairs were not significantly different between older and young adults.

Condition signature for people with PD (PD vs. OA) had only three black colored cells (maximal cross-correlation: LH vs. RH, LK vs. RK, LHv vs. RHv) among the bilateral joint couplings. However, SROD analysis indicated that the PD group had significantly greater total SROD values for hip, knee, and ankle joints compared to young adults group. These results suggest that shapes of bilateral joint variables were similar although angular differences of bilateral joint pairs were significantly greater between the PD group and older adults group.

Asynchrony of joint coupling patterns during gait can be associated with musculoskeletal injuries (Tiberio, 1987, Hamill et al., 1999, DeLeo et al., 2004). During continuous walking, abnormal joint coupling patterns (deviations in joint coupling patterns from normative data) can be considered as a perturbation assuming that normative gait has minimal disturbance. Although a small amount of perturbation is applied to human gait, it can result in falls unless gait is controlled toward a steady state trajectory. In Condition Signature Analysis, black colored cells indicate different joint coupling patterns compared to the normative data set. Both older adult and people with PD groups had many different joint coupling patterns from the healthy adults.

1 These results indicate that both groups accommodate a significant amount of disturbance during
2 gait, which may be associated with increased gait imbalance.

4 **5. Conclusion**

5 In summary, new gait assessment tools were applied to the three participant groups (YA,
6 OA, PD) for the purpose of characterizing gait behavior due to aging and neurological disease
7 such as PD. These techniques successfully captured changes in various aspects of gait behaviors
8 such as asymmetry, complexity, and joint coupling patterns. These tools provide a variety of
9 quantitative assessments of gait patterns. The ROD analysis can be used to detect specific areas
10 of the gait cycle affected by neuromuscular diseases or other gait impairments. Change in
11 fluctuation frequency and irregularity of kinematic data due to various gait disturbances can be
12 quantitatively assessed using variability and complexity measures presented in this study. The
13 CSA offers a visually accessible way to examine comprehensively multiple joint coupling
14 patterns of a certain gait behavior at a glance. Greater understanding of how these different gait
15 behaviors vary with different clinical populations can be used to diagnose gait impairment due to
16 musculoskeletal disease and neurological disorder, and possibly track gait impairment
17 progression. Especially, Condition Signature Analysis will be helpful to build a database which
18 would be useful to build statistical models to map certain gait characteristics with associated
19 musculoskeletal or neurological disorders. With sufficient human motion data from a variety of
20 population groups, Condition Signature Analysis could guide health-care professionals in
21 assessing and diagnosing pathologies related to human motion due to the presence of diverse
22 neuromuscular disorders such as PD. In order that these tools would be clinically useful, future

work considering a variety of pathological gait patterns is required. Future study should determine if certain pathologies result in clinically useful condition signatures. Condition signatures might be generated using different kinematic variables such as upper extremity joint angles or kinetic variables such as ground reaction forces and joint moments.

Acknowledgments

This work was supported by funding from NSF grant # 0727083 (Hsiao-Wecksler), University of Illinois Campus Research Board (Hsiao-Wecksler, Park), and National Parkinson's foundation Center for Excellence at University of Florida (Hass). We thank Dr. Srikant Vallabhajosula for the data collection, and Luke Jungles who helped with data processing.

References

- Ashburn, A., Stack, E., Pickering, R. M., Ward, C. D., 2001. A community-dwelling sample of people with Parkinson's disease: characteristics of fallers and non-fallers. *Age Ageing* 30, 47-52.
- Bautmans, I., Jansen, B., Van Keymolen, B., Mets, T., 2011. Reliability and clinical correlates of 3D-accelerometry based gait analysis outcomes according to age and fall-risk. *Gait Posture* 33, 366-372.
- Blin, O., Ferrandez, A. M., Serratrice, G., 1990. Quantitative analysis of gait in Parkinson patients: increased variability of stride length. *J. Neurol. Sci.* 98, 91-97.
- Danion, F., Varraine, E., Bonnard, M., Pailhous, J., 2003. Stride variability in human gait: the effect of stride frequency and stride length. *Gait Posture* 18, 69-77.
- Deleo, A. T., Dierks, T. A., Ferber, R., Davis, I. S., 2004. Lower extremity joint coupling during running: a current update. *Clin Biomech* 19, 983-991.
- Devita, P., Hortobagyi, T., Barrier, J., Torry, M., Glover, K. L., Speroni, D. L., Money, J., Mahar, M. T., 1997. Gait adaptations before and after anterior cruciate ligament reconstruction surgery. *Med. Sci. Sports Exerc.* 29, 853-859.
- Diberardino, L. A., Polk, J. D., Rosengren, K. S., Spencer-Smith, J. B., Hsiao-Wecksler, E. T., 2010. Quantifying complexity and variability in phase portraits of gait. *Clin Biomech* 25, 552-556.
- Diberardino, L. A., Ragetly, C. A., Hong, S., Griffon, D. J., Hsiao-Wecksler, E. T., 2012. Improving regions of deviation gait symmetry analysis with pointwise T tests. *J Appl Biomech* 28, 210-214.
- Diop, M., Rahmani, A., Belli, A., Gautheron, V., Geyssant, A., Cottalorda, J., 2004. Influence of speed variation and age on the asymmetry of ground reaction forces and stride parameters of normal gait in children. *Journal of Pediatric Orthopaedics B* 13, 308-314.
- Duysens, J., Van De Crommert, H. W. a. A., 1998. Neural control of locomotion; Part 1: The central pattern generator from cats to humans. *Gait Posture* 7, 131-141.
- Hamill, J., Van Emmerik, R. E. A., Heiderscheit, B. C., Li, L., 1999. A dynamical systems approach to lower extremity running injuries. *Clin Biomech* 14, 297-308.
- Hausdorff, J. M., 2004a. Stride variability: beyond length and frequency. *Gait Posture* 20, 304.
- Hausdorff, J. M., 2004b. Stride variability: beyond length and frequency. *Gait Posture* 20, 304-304.
- Hausdorff, J. M., Rios, D. A., Edelberg, H. K., 2001. Gait variability and fall risk in community-living older adults: A 1-year prospective study. *Arch. Phys. Med. Rehabil.* 82, 1050-1056.
- Johnell, O., Melton, J., Atkinson, E., O'fallon, M., Kurland, L., 1992. Fracture Risk in Patients with Parkinsonism: A Population-based Study in Olmsted County, Minnesota. *Age Ageing* 21, 32-38.
- Knoll, Z., Kocsis, L., Kiss, R., 2004. Gait patterns before and after anterior cruciate ligament reconstruction. *Knee Surg. Sports Traumatol. Arthrosc.* 12, 7-14.
- Lewek, M. D., Poole, R., Johnson, J., Halawa, O., Huang, X., 2010. Arm swing magnitude and asymmetry during gait in the early stages of Parkinson's disease. *Gait Posture* 31, 256-260.
- Lipsitz, L. A., 2002. Dynamics of stability: the physiologic basis of functional health and frailty.

1 J. Gerontol. A. Biol. Sci. Med. Sci. 57, B115-125.

2 Lipsitz, L. A. ,Goldberger, A. L., 1992. Loss of 'Complexity' and Aging. JAMA: The Journal of
3 the American Medical Association 267, 1806-1809.

4 Miller, R., Thaut, M., McIntosh, G. ,Rice, R.: 1996. Components of EMG symmetry and
5 variability in parkinsonian and healthy elderly gait.

6 Munoz-Diosdado, A., Del Rio Correa, J. L. ,Brown, A. F. Multifractality in time series of human
7 gait. Engineering in Medicine and Biology Society, 2003. Proceedings of the 25th
8 Annual International Conference of the IEEE, 17-21 Sept. 2003 2003. 1792-1795 Vol.2.

9 Owings, T. M. ,Grabiner, M. D., 2004. Step width variability, but not step length variability or
10 step time variability, discriminates gait of healthy young and older adults during treadmill
11 locomotion. J. Biomech. 37, 935-938.

12 Park, K., Dankowicz, H. ,Hsiao-Weckslar, E. T., 2012. Characterization of spatiotemporally
13 complex gait patterns using cross-correlation signatures. Gait Posture 36, 120-126.

14 Schaafsma, J. D., Giladi, N., Balash, Y., Bartels, A. L., Gurevich, T. ,Hausdorff, J. M., 2003. Gait
15 dynamics in Parkinson's disease: relationship to Parkinsonian features, falls and response
16 to levodopa. J. Neurol. Sci. 212, 47-53.

17 Schwartz, M. H., Rozumalski, A. ,Trost, J. P., 2008. The effect of walking speed on the gait of
18 typically developing children. J. Biomech. 41, 1639-1650.

19 Sheridan, M. R., Flowers, K. A. ,Hurrell, J., 1987. Programming and execution of movement in
20 Parkinson's disease. Brain 110 (Pt 5), 1247-71.

21 Shorter, K. A., Polk, J. D., Rosengren, K. S. ,Hsiao-Weckslar, E. T., 2008. A new approach to
22 detecting asymmetries in gait. Clin Biomech 23, 459-467.

23 Tiberio, D., 1987. The effect of excessive subtalar joint pronation on patellofemoral mechanics: a
24 theoretical model. J. Orthop. Sports Phys. Ther. 9, 160-5.

25 Uitti, R. J., Baba, Y., Whaley, N. R., Wszolek, Z. K. ,Putzke, J. D., 2005. Parkinson disease.
26 Neurology 64, 1925-1930.

27 Yogev, G., Plotnik, M., Peretz, C., Giladi, N. ,Hausdorff, J., 2007. Gait asymmetry in patients
28 with Parkinson's disease and elderly fallers: when does the bilateral coordination of gait
29 require attention? Exp. Brain Res. 177, 336-346.

30 Yust-Katz, S., Tesler, D., Treves, T. A., Melamed, E. ,Djaldetti, R., 2008. Handedness as a
31 predictor of side of onset of Parkinson's disease. Parkinsonism & Related Disorders 14,
32 633-635.

Table 1. Mean (and standard deviation) values of symmetry region of deviation (SROD) measures for three bilateral joint pairs for three different groups (YA: healthy young adult, OA: healthy old adult, PD: people with PD). Superscript letters denote significant difference from indicated group ($p < 0.05$).

SROD measure (units)	Hip			Knee			Ankle		
	YA (A)	OA (B)	PD (C)	YA (A)	OA (B)	PD (C)	YA (A)	OA (B)	PD (C)
Peak value	2.1 ^C	3.4	5.2 ^A	2.7 ^{BC}	9.4 ^A	12.4 ^A	3.0 ^C	2.8 ^C	6.6 ^{AB}
(degree)	(2.2)	(2.1)	(2.6)	(2.1)	(6.8)	(7.4)	(2.5)	(1.1)	(4.8)
Peak timing	64.3	63.6	38.1	38.4 ^B	72.3 ^A	43.2	56.7	43.6	58.2
(% GC)	(34.5)	(29.4)	(32.6)	(30.8)	(30.8)	(35.9)	(29.7)	(38.3)	(22.3)
Total SROD	60.3 ^C	107.8 ^C	239.9 ^{AB}	62.2 ^{BC}	290.0 ^{AC}	488.0 ^{AB}	83.4 ^C	66.4 ^C	182.9 ^{AB}
(degree·% GC)	(76.8)	(106.1)	(191.1)	(57.1)	(248.9)	(243.4)	(85.3)	(23.6)	(154.5)

Table 2. Mean (and standard deviation) values of individual region of deviation (IROD) measures for each lower limb joint for three different groups. Superscript letters denote significant difference from indicated group ($p < 0.05$).

Lower extremity joints	IROD Measure (unit)	Left leg			Right leg		
		YA (A)	OA (B)	PD (C)	YA (A)	OA (B)	PD (C)
Hip	Peak value (degree)	6.7 ^{BC} (2.9)	20.0 ^A (7.0)	13.9 ^A (8.6)	6.4 ^{BC} (2.3)	18.6 ^A (7.9)	11.8 ^A (7.3)
	Peak timing (% GC)	62.9 ^B (22.8)	30.0 ^A (42.2)	42.5 (39.7)	52.1 ^B (29.3)	20.4 ^A (35.5)	50 (29.9)
	Total IROD (degree·% GC)	319 ^{BC} (222)	1111 ^A (544)	826 ^A (743)	284 ^{BC} (195)	1068 ^A (584)	757 ^A (700)
	Peak value (degree)	7.9 ^{BC} (3.2)	14.5 ^A (7.4)	18.6 ^A (5.4)	7.3 ^{BC} (3.0)	20.0 ^A (12.5)	17.9 ^A (13.9)
	Peak timing (% GC)	46.8 ^{BC} (33.2)	81.7 ^A (23.3)	81.2 ^A (13.8)	51.1 (33.3)	70.1 (27.2)	60.9 (36.6)
Knee	Total IROD (degree·% GC)	288 ^{BC} (183)	504 ^A (259)	703 ^A (274)	247 ^{BC} (140)	820 ^A (572)	620 ^A (452)
	Peak value (degree)	7.1 ^C (4.1)	9.5 (2.1)	11.8 ^A (4.4)	7.6 ^C (3.3)	9.9 (2.8)	12.3 ^A (4.0)
	Peak timing (% GC)	63.5 ^B (29.9)	31.1 ^A (30.9)	43.1 (29.8)	57.1 ^B (24.8)	9.9 ^A (2.8)	43.4 (29.0)
	Total IROD (degree·% GC)	211 ^{BC} (145)	479 ^A (128)	457 ^A (196)	214 ^{BC} (131)	453 ^A (152)	457 ^A (113)
	Peak value (degree)	7.1 ^C (4.1)	9.5 (2.1)	11.8 ^A (4.4)	7.6 ^C (3.3)	9.9 (2.8)	12.3 ^A (4.0)
Ankle	Peak timing (% GC)	63.5 ^B (29.9)	31.1 ^A (30.9)	43.1 (29.8)	57.1 ^B (24.8)	9.9 ^A (2.8)	43.4 (29.0)
	Total IROD (degree·% GC)	211 ^{BC} (145)	479 ^A (128)	457 ^A (196)	214 ^{BC} (131)	453 ^A (152)	457 ^A (113)
	Peak value (degree)	7.1 ^C (4.1)	9.5 (2.1)	11.8 ^A (4.4)	7.6 ^C (3.3)	9.9 (2.8)	12.3 ^A (4.0)
	Peak timing (% GC)	63.5 ^B (29.9)	31.1 ^A (30.9)	43.1 (29.8)	57.1 ^B (24.8)	9.9 ^A (2.8)	43.4 (29.0)
	Total IROD (degree·% GC)	211 ^{BC} (145)	479 ^A (128)	457 ^A (196)	214 ^{BC} (131)	453 ^A (152)	457 ^A (113)

Table 3. Mean (and standard deviation) values of complexity and variability measures for lower limb joints for three different groups. Superscript letters denote significant difference from indicated group ($p \leq 0.006$).

Lower extremity joints	Measure (unit)	Left leg			Right leg		
		YA (A)	OA (B)	PD (C)	YA (A)	OA (B)	PD (C)
Hip	Complexity (# harmonic)	192 ^{BC} (18)	149 ^A (35)	153 ^A (31)	190 ^{BC} (17)	148 ^A (29)	158 ^A (24)
	Drift (Cartesian distance)	0.72 (0.24)	0.80 (0.38)	0.74 (0.33)	0.82 (0.22)	0.80 (0.23)	0.84 (0.48)
	Area (rad ² /s)	0.0064 (0.0038)	0.0105 (0.0067)	0.0132 (0.0147)	0.0079 (0.0045)	0.0096 (0.0049)	0.0181 (0.0230)
Knee	Complexity (# harmonic)	179 (14)	182 (17)	173 (11)	176 (16)	192 (27)	186 (18)
	Drift (Cartesian distance)	1.01 (0.45)	0.78 (0.26)	1.25 (0.94)	1.18 (0.56)	0.71 (0.23)	1.36 (1.13)
	Area (rad ² /s)	0.0124 (0.0097)	0.0090 (0.0057)	0.0211 (0.0265)	0.0156 (0.0111)	0.0073 (0.0044)	0.0525 (0.0891)
Ankle	Complexity (# harmonic)	272 ^C (22)	260 ^C (14)	222 ^{AB} (30)	275 ^C (26)	261 ^C (18)	225 ^{AB} (27)
	Drift (Cartesian distance)	1.00 (0.54)	0.59 (0.15)	0.86 (0.46)	0.85 (0.31)	0.67 (0.25)	0.97 (0.52)
	Area (rad ² /s)	0.0083 (0.0065)	0.0055 (0.0022)	0.0133 (0.0169)	0.0071 (0.0057)	0.0057 (0.0029)	0.0172 (0.0225)

1 **Figures**

2 **Figure 1:** *Condition signatures* indicating significant differences of joint coupling patterns. (a)
3 older adults vs. young adults, (b) people with PD vs. older adults. Boxes shaded black mean
4 indicate statistically significant differences ($p < 0.05$), but white boxes indicate no differences in
5 cell values between the two conditions.

6

7 *Note: Angular displacements; LH = left hip, LK = left knee, LA = left ankle, RH = right hip,
8 RK = right knee, RA = right ankle, Angular velocities; LHv = left hip, LKv = left knee, LAv =
9 left ankle, RHv = right hip, RKv = right knee, RAv = right ankle).

1

(a)

	LH	LK	LA	RH	RK	RA	LHv	LKv	LAv	RHv	RKv	RAv
LH	—											
LK		—										
LA			—									
RH				—								
RK					—							
RA						—						
LHv							—					
LKv								—				
LAv									—			
RHv										—		
RKv											—	
RAv												—

(b)

	LH	LK	LA	RH	RK	RA	LHv	LKv	LAv	RHv	RKv	RAv
LH	—											
LK		—										
LA			—									
RH				—								
RK					—							
RA						—						
LHv							—					
LKv								—				
LAv									—			
RHv										—		
RKv											—	
RAv												—

2