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Interlimb coordination is impaired during walking in persons with Parkinson's disease

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Abstract

Background—Coordination between the upper and lower extremities is important to providing dynamic stability during human gait. Though limited, previous research has suggested that interlimb coordination may be impaired in persons with Parkinson's disease. We extend this previous work using continuous analytical techniques to enhance our understanding of interlimb coordination during gait in persons with Parkinson's disease.

Methods—Eighteen adults with Parkinson's disease and fifteen healthy older adults walked overground while undergoing three-dimensional motion capture. Ipsilateral and contralateral interlimb coordination between the sagittal shoulder and hip angles was assessed using cross-covariance techniques. Independent samples and paired samples t-tests compared measures of interlimb coordination between groups and between sides within the participants with Parkinson's disease, respectively. Pearson's correlations were applied to investigate associations between interlimb coordination measures and subscores of gait, posture, and bradykinesia on the Unified Parkinson's Disease Rating Scale.

Findings—Ipsilateral and contralateral interlimb coordination was reduced in persons with Parkinson's disease compared to the healthy older adults. Ipsilateral coordination between the upper and lower extremities more affected by disease was found to be negatively associated with clinical scores of gait and posture. Interlimb coordination was not significantly associated with clinical measures of bradykinesia.

Interpretation—Persons with Parkinson's disease exhibit reduced interlimb coordination during gait when compared to healthy older adults. These reductions in coordination are related to clinically-meaningful worsening of gait and posture in persons with PD and coordination of arm and leg movements should be considered in future research on gait therapy in this population.

Keywords

Parkinson's disease; gait; interlimb coordination; cross-covariance

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Introduction

Much of the research on human gait has focused primarily on lower extremity function. Arm movements however, are also important due to their role in increasing metabolic efficiency (Collins et al., 2009) and in maintaining stability during gait (Hinrichs and Cavanaugh, 1981; Bruijn et al., 2010). This is accomplished by reducing whole-body angular momentum around the vertical axis (Elftman, 1939; Park, 2008). Healthy individuals typically walk with arm swing coupled to the motion of the legs. At slower walking speeds, the arms swing in-phase with one another and at a 2:1 ratio with swing of the legs. As walking speed increases, the arms and legs begin to swing at a 1:1 ratio as the arms swing out-of-phase with each other and in-phase with the contralateral leg (Wagenaar and van Emmerik, 2000; Donker et al., 2001). It is important that upper and lower extremity movements remain tightly coordinated during gait, as disruptions in interlimb coordination between the upper and lower extremities have been associated with a decline in walking speed (Meyns et al., 2012; Kwakkel and Wagenaar, 2002) and dynamic stability with respect to control of center of mass during gait (Krasovsky et al., 2012). Therefore, interlimb coordination may be particularly important to maintaining stability in individuals with gait and postural instability such as persons with Parkinson's disease (PD). PD gait disturbance and postural instability are well documented and lead to the troubling finding that approximately 50–70% of persons with PD experience falls during the course of their disease (Wood et al., 2002; Pickering et al., 2007).

PD is characterized by asymmetric motor deficits in both the upper and lower extremities resulting from degeneration of dopaminergic neurons within the basal ganglia. Prior investigators have observed that arm swing is asymmetric (Lewek et al., 2009; Huang et al., 2012) and diminished arm swing has been suggested as a predictor of falls in persons with PD (Wood et al., 2002). Asymmetric changes in arm swing accompanied by asymmetric changes in gait would suggest that interlimb coordination may also be affected by PD. Indeed, electromyographical analyses have suggested that coordination of upper and lower extremity movements may be reduced during gait in persons with PD (Dietz and Michel, 2008). Yet, previous kinematic analyses in PD have by-and-large quantified interlimb coordination using discrete analytical measures yielding limited and mixed results. Discrete analysis of interlimb patterns in persons with PD have been suggested to be significantly influenced by the limb combination being analyzed; that is, coordination patterns between the ipsilateral arm and leg on the side more affected by PD are reduced compared to controls during treadmill walking (Nanhoe-Mahabier et al., 2011). However, coordination between the less affected arm and leg was not reduced in PD, nor were any differences in ipsilateral or contralateral interlimb coordination observed between non-freezing persons with PD and controls during overground gait.

Though discrete measures of interlimb coordination are insightful, they are inherently limited to describing data at individual points in time. This limitation may explain the lack of significant differences observed in persons with PD when compared to controls in previous studies. As suggested by Krasovsky and Levin (Krasovsky and Levin, 2010), discrete analyses of coordination are limited to one point in time along the entire gait cycle and do not allow for detection of transient differences in two time series signals, while continuous methods provide increased temporal resolution into interlimb coordination patterns. Therefore, we can assess these patterns as dynamical systems which change over time to better understand the coupling of the upper and lower extremities during gait in PD. Certainly, neuromuscular control of gait is disrupted throughout the gait cycle in persons with PD, as parkinsonian gait is characterized by continuous deficits including arrhythmic stepping (Baltadjieva et al., 2006), increased stride-to-stride variability (Blin et al., 1990), and pronounced asymmetry (Yogev et al., 2007). Thus, we postulate that the use of

continuous analyses may afford the sensitivity to detect side-specific differences in interlimb coordination in PD when compared to healthy older adults.

While mild impairment of upper and lower extremity coordination has been noted in persons with PD relative to controls (Nanhoe-Mahabier et al., 2011), little is known about the clinical impact of disrupted interlimb coordination on gait and motor performance within this population. One previous study suggested that deterioration of arm and leg coupling during gait is negatively associated with clinical scores of bradykinesia and rigidity in PD (Winogrodzka et al., 2005) and others propose that coordinated arm swing is important to maintaining gait stability in response to external perturbations in older adults (Bruijn et al., 2010; Krasovsky et al., 2012). Previous literature on coordination of the upper and lower extremities during gait in individuals post-stroke also suggests that decreased ipsilateral coordination of the hemiparetic arm and leg is a limiting factor as clinicians attempt to restore walking speed in these individuals (Kwakkel and Wagenaar, 2002). Further, a study of children with cerebral palsy demonstrated that, while increasing walking speed had little effect on the interlimb coordination of typically-developing children, increasing walking speed on a treadmill significantly improved coordination in the children with cerebral palsy (Meyns et al., 2012). However, relationships between diminished interlimb coordination and global gait and postural function in persons with PD have yet to be studied.

The purpose of this study was to compare interlimb coordination during gait in optimally-treated persons with PD and neurologically-healthy aged-matched adults by applying continuous techniques. We also aimed to assess associations between interlimb coordination and clinically-relevant gait, postural, and bradykinetic features of PD. We hypothesized that coordination would be reduced in persons with PD when compared to controls. We also expected that the reductions in interlimb coordination would accompany reductions in arm swing during gait and would be associated with subscores of gait, posture, and bradykinesia on the Unified Parkinson's Disease Rating Scale (UPDRS).

Methods

Prior to testing, all subjects read and signed an informed consent form approved by the University's Institutional Review Board. Eighteen adults with mild-to-moderate PD (mean age 63.5 (SD 8.93) years; mean mass 76.5 (SD 13.7) kg; mean height 1.69 (SD 0.09) m, mean overground gait speed 1.14 (SD 0.12) m/s, mean UPDRS motor score 22.7 (SD 7.38)) and fifteen age-matched healthy older adults (mean age 63.7 (SD 8.29), mean mass 74.1 (SD 14.7) kg; mean height 1.70 (SD 0.11) m, mean overground gait speed 1.20 (SD 0.11) m/s) were recruited for the study. Diagnosis of PD was made by a movement disorders-trained neurologist based on UK Brain Bank criteria. Persons with PD who experienced freezing of gait were excluded. Participants walking less than .80 m/s were also excluded from the study, as this rate has been suggested as the threshold at which the ratio between the swing of the arms and legs changes from a 1:1 ratio toward a 2:1 ratio (Wagenaar and van Emmerik, 2000). None of the participants included walked slower than .93 m/s. UPDRS scales were recorded on video and rated by an independent, movement disorder-trained neurologist. A total bradykinesia score was calculated for each side by summing facial expression, finger taps, hand movements, rapid alternating hand movements, leg agility, arising from chair, and body bradykinesia (Winogrodzka et al., 2005). Because the UPDRS was rated on video, subscores for rigidity were not included. Thirty-five passive retroreflective markers were placed over bony landmarks according to the Vicon Plug-in-Gait marker set. Kinematic data were recorded as each subject performed ten overground gait trials along an 8-m walkway surrounded by a multi-camera optical motion capture system (120 Hz; Vicon Nexus, Lake Forest, California). Gait cycles were defined as the time between two

consecutive heel-strikes of the same limb. Heel-strikes were manually labeled using Vicon Nexus software based on marker trajectory profiles.

Bilateral hip and shoulder sagittal joint angles were calculated within Vicon Nexus as the relative angles between the thigh/pelvis and upper arm/thorax segments, respectively (Kadaba et al., 1990). Custom MATLAB software was then used to calculate cross-covariance coefficients and between the hip and shoulder joint angle vectors (contralateral and ipsilateral) as well as the range of motion (ROM) of the shoulder and hip joints. Cross-covariance is a continuous measure of the similarity with which two time-series vectors change relative to one another. One advantage to this technique relative to other continuous analyses of time-series signals is the opportunity to investigate coordination patterns along a series of temporal shifts in the data, allowing for interpretation as to whether the two signals are different in shape and/or temporal alignment. Cross-covariance techniques are similar to the cross-correlation techniques which have been recently used to investigate interlimb coordination patterns (Park et al., 2012; Huang et al., 2012) with the exception that the time-series vectors are demeaned when calculating cross-covariance coefficients. When demeaning the time-series vectors, the mean value of the vector as a whole is simply subtracted from each individual point along the vector. This biases the calculation toward temporal covariance between the signals by reducing the influence of changes in signal amplitude (in this study, joint angle magnitude). Cross-covariance was selected rather than cross-correlation for this study as it was important to demean the joint angle vectors being compared due to the fact that the ROM of the hips and shoulders are typically dissimilar in magnitude. Thus, cross-covariance coefficients were calculated using the following traditional equation (Orfanidis, 1996):

$$CCC(X, Y) = E[(X - \mu_X)(Y - \mu_Y)^*]$$

where E indicates the expected value, X and Y are two different joint angle vectors (for example, ipsilateral shoulder and hip angles), and μ_X and μ_Y are the means of these joint angle vectors, respectively. Thus, the cross-covariance coefficient is determined by calculating the expected value of the complex conjugate of the product of the two demeaned time-series joint angle vectors. One of the vectors X and Y can then be temporally shifted relative to the other to obtain different interpretations of the coordination between the two vectors. The temporally-shifted vector “slides” one data point at a time until a coefficient is calculated for every possible temporal alignment between the two vectors. For instance, if we consider two vectors each with 100 data points, we will obtain a resulting vector with 199 coefficients, with the 100th coefficient corresponding to zero time lag. In this study, both the cross-covariance coefficients at zero time lag (CCC0 - the coefficient corresponding to the physiological signal i.e. when no temporal shift is applied to either joint angle vector) and the maximal cross-covariance coefficient (CCC Max) are reported. CCC0 and CCC Max values are normalized to a range between -1 (perfectly out-of-phase) and 1 (perfectly in-phase), with a value of zero indicating no covariance between signals.

CCC0, CCC Max, and ROM were calculated for each individual stride cycle across the ten overground gait trials and then averaged within each subject. Trials were excluded if the arms voluntarily moved out of rhythmic swing (i.e. the participant touched their face or scratched an itch, for instance). CCC0, CCC Max, and ROM were averaged between sides in the controls to create a singular control value for each measure. For example, right hip/left shoulder CCC0 and left hip/right shoulder CCC0 were averaged to create contralateral CCC0 in the controls participants. Independent samples t-tests compared CCC0, CCC Max, and ROM in the controls group with each side combination in the PD group individually. The more affected and less affected sides were determined based on self-reported side of

onset and confirmed through UPDRS scores. Cohen's d effect sizes were calculated for each CCC0 and CCC Max comparison to ease interpretability of the magnitude differences observed. We also applied paired t -tests to analyze side differences in CCC0, CCC Max, and ROM within the PD group (i.e. more affected shoulder/less affected hip vs. less affected shoulder/more affected hip). One-tailed Pearson's correlations were applied to analyze associations between interlimb coordination measures and relevant UPDRS motor subscores for gait and posture. Levels of significance for all t -tests and correlations were set at $\alpha=.05$ (SPSS 20, IBM, Armonk, New York).

Results

Interlimb Coordination Comparisons between PD and Controls

Walking speed was not significantly different between groups. ROM was significantly reduced in the more affected hip in PD but not in the less affected hip when compared to healthy controls (less affected hip: mean 41.45 (SD 4.96)°, more affected hip: mean 39.46 (SD 4.68)° vs. controls: mean 43.64 (SD 3.04)°; $p=.097$ and $.004$, respectively). Range of motion was not reduced in either shoulder in PD as compared to controls (Figure 1).

Ipsilateral CCC0 was significantly reduced in both sides in PD compared to controls (less affected shoulder/less affected hip: mean $-.901$ (SD $.056$), more affected shoulder/more affected hip: mean $-.860$ (SD $.109$) vs. controls: mean $-.932$ (SD $.026$); $p=.047$ and $.014$, Cohen's $d=.709$ and $.896$, respectively). Ipsilateral CCC Max was significantly reduced in the more affected side but not the less affected side in PD compared to controls (less affected shoulder/less affected hip: mean $-.930$ (SD $.046$), more affected shoulder/more affected hip: mean $-.905$ (SD $.089$) vs. controls: mean $-.953$ (SD $.016$); $p=.056$ and $.038$, Cohen's $d=.676$ and $.737$, respectively).

Contralateral CCC0 was significantly reduced in the less affected hip/more affected shoulder combination in PD but not in the more affected hip/less affected shoulder combination when compared to controls (less affected hip/more affected shoulder: mean $.885$ (SD $.073$), more affected hip/less affected shoulder: mean $.917$ (SD $.076$) vs. controls: mean $.937$ (SD $.031$); $p=.011$ and $.304$, Cohen's $d=.930$ and $.354$, respectively). Contralateral CCC Max (less affected hip/more affected shoulder: mean $.922$ (SD $.070$), more affected hip/less affected shoulder: mean $.949$ (SD $.048$) vs. controls: mean $.960$ (SD $.021$); $p=.040$ and $.384$, Cohen's $d=.729$ and $.300$, respectively) was also significantly reduced in the less affected hip/more affected shoulder combination in PD but not in the more affected hip/less affected shoulder combination when compared to controls (Figure 2).

Interlimb Coordination Comparisons between Sides within PD

ROM was significantly reduced in the more affected hip when compared to the less affected hip (less affected hip: mean 41.45 (SD 4.97)° vs. more affected hip: mean 39.47 (SD 4.69)°, $p=.016$). ROM of the shoulder joint was not significantly different between the more affected and less affected sides (Figure 1). We did not observe any differences in CCC0, or CCC Max between the more affected and less affected sides within PD (Figure 2).

Correlations between UPDRS Subscores and Interlimb Coordination Measures within PD

We observed a significant negative association between UPDRS subitem 28 (posture) and ipsilateral CCC0 on the more affected side ($r=-0.433$, $p=.036$). A negative association between UPDRS subitem 28 and ipsilateral CCC Max was also nearly significant ($r=-0.374$, $p=.063$). We also observed a significant negative association between UPDRS subitem 29 (gait) and ipsilateral CCC0 on the more affected side ($r=-0.406$, $p=.047$) while the negative association between UPDRS subitem 29 and ipsilateral CCC Max on the more affected side

was also nearly significant ($r=-0.328$, $p=.092$). We did not observe significant associations between UPDRS subitems 28 or 29 and any other interlimb coordination combinations nor did we observe any correlations between interlimb coordination and the total bradykinesia scores.

Discussion

Despite the apparent lack of findings regarding the effects of PD on discrete interlimb coordination in previous literature, several previous studies have suggested that coordination between the upper and lower extremities during gait may be disrupted (van Emmerik and Wagenaar, 1996; Dietz and Michel, 2008). Indeed, we observed reduced interlimb coordination in persons with PD when compared to healthy age-matched controls after applying continuous analytical techniques (CCC0, CCC Max). CCC0 appeared to be particularly sensitive to differences in interlimb coordination, as ipsilateral CCC0 values were reduced bilaterally in persons with PD. Further, we observed a reduction in contralateral interlimb coordination between the hip of the less affected side and shoulder of the more affected side in PD. Effect sizes demonstrated that the differences observed in these measures were relatively large. Our results also suggest that interlimb coordination on the side more affected by PD is related to decreased performance on clinical scales of gait and posture. However, contrary to our hypotheses, we did not detect differences in ROM of the shoulder joint during gait between controls and medicated persons with PD nor did we detect associations between interlimb coordination and clinical scores of bradykinesia.

Our findings demonstrate an important association between clinically-relevant performance on the gait and posture items of the UPDRS and ipsilateral coordination of the more affected arm and leg in PD, which was substantiated by a large effect size when compared to controls. These findings mirror observations that coordination during gait in children with cerebral palsy is also limited by the side more affected by disease (Meyns et al., 2012). In the present study, we also noted diminished contralateral coordination between the more affected shoulder and the less affected hip. Similarly, Meyns and colleagues noted that alterations in interlimb coordination appeared to result specifically from dysfunction of the more affected arm in the hemiplegic children (Meyns et al., 2012). In sum, both studies suggest interlimb coordination may be limited by dysfunction of the more affected arm in neurological populations characterized by motor asymmetry and that impaired coordination is related to global gait dysfunction.

The current study also adds to the evidence suggesting that supraspinal dysfunction in PD affects motor function controlled within the spinal cord. The rhythmic coupling of the swing of the arms and legs is typically thought to be governed by central pattern generators within the spinal cord (Zehr and Duysens, 2004; Dietz and Michel, 2008). Structures within the midbrain locomotor region, particularly the pedunculopontine nucleus, interact with the basal ganglia (Jahn et al., 2008) and are thought to mediate activity of the spinal central pattern generators (Pierantozzi, 2008). Indeed, the pedunculopontine nucleus has recently gained considerable attention as a target for deep brain stimulation therapy to improve gait function in PD (Thevathasan et al., 2011; Ferraye et al., 2010). Thus, we postulate that the dysfunction of the basal ganglia and pedunculopontine nucleus resulting from PD likely contributes to the relative incoordination observed between the upper and lower extremities in this study. Further research should investigate the effects of deep brain stimulation of the pedunculopontine nucleus on interlimb coordination in persons with PD.

It is notable that evidence of rigidity was observed in the gait behavior of participants with PD, as the ROM of the hips was asymmetric. van Emmerik and colleagues have previously suggested that axial rigidity reduces the ability to coordinate trunk movements during gait in

persons with PD (van Emmerik et al., 1999). Moreover, recent findings have demonstrated improvement of interlimb coordination after deep brain stimulation of the subthalamic nucleus, which has been shown to significantly reduce rigidity and improve gait speed (Crenna et al., 2008). Coupling these results with evidence relating interlimb coordination to walking speed in populations of post-stroke individuals (Kwakkel and Wagenaar, 2002) and children with cerebral palsy (Meyns et al., 2012), it seems that interventions which emphasize both arm and leg movement speed may be important to improve interlimb coordination in persons with PD. Though additional research on the mechanisms of reduced interlimb coordination in PD is certainly required, the current study also provides further support to the notion that arm-leg coupling should not be ignored but rather considered an important point of emphasis in surgical and exercise-based gait therapies designed for persons with PD.

Continuous measures of coordination are becoming increasingly popular in the gait literature especially when analyzing coordination patterns between multiple time-series vectors. Certainly, disruptions in coordination may occur at any number of points in time along the gait cycle. Using discrete analyses, the techniques are limited in such a way that areas within the gait cycle where coordination is disrupted may not coincide with the target regions of the analyses (in most interlimb coordination studies, joint angle maxima and minima) and thus the coordination patterns appear unaffected. Therefore, continuous techniques are becoming preferred due to their intrinsic abilities to analyze and compare the vectors of interest in their entirety, as opposed to point estimates which ignore a vast majority of the available data. For instance, Park and colleagues have recently applied cross-correlation techniques (which are very similar to the cross-covariance analyses applied in the present study) to investigate the effects of wearing a knee brace on bilateral joint angle profiles (Park et al., 2012) while Huang and colleagues have applied a similar analysis to investigate coordination in arm swing in persons with PD (Huang et al., 2012). Our results provide further support for the use of continuous measures when assessing coordination patterns, as we observed differences in ipsilateral interlimb coordination between controls and persons with PD which were not previously observed using discrete measures.

This study was limited to persons with only mild-to-moderate PD who were optimally-treated with dopaminergic medication at the time of testing. Thus, we cannot speculate as to the effects of such therapy nor did we study a wide sample from which to assess the effects of disease severity on interlimb coordination in persons with PD. The participants in the present study were also only tested during overground gait and not during treadmill walking. As gait patterns have been previously shown to differ between overground walking and treadmill walking (Riley et al., 2007), mechanisms through which treadmill walking may alter interlimb coordination in persons with PD remain unknown. Indeed, coordination has previously been shown to be altered during treadmill gait when compared to overground gait in both PD (Nanhoe-Mahabier et al., 2011) and healthy participants (Carpinella et al., 2010). Further, on average, fewer strides were analyzed for each participant when compared to treadmill walking studies due to the intrinsic limitations of overground gait research. As we omitted participants walking slower than .80 m/s from both groups, we can confidently conclude that the diminished coupling between the upper and lower extremities observed in this study indeed arise from motor deficits of PD and not simply a manipulation in walking speed (van Emmerik and Wagenaar, 1996; Wagenaar and van Emmerik, 2000).

Conclusion

In the present study, interlimb coordination was assessed in persons with PD and compared to controls using continuous (CCC0, CCC Max) measures. We observed differences in ipsilateral and contralateral coordination in persons with PD when compared to controls.

Ipsilateral coordination on the side more-affected by PD was also negatively associated with UPDRS gait and postural scores. The results of this study suggest that interlimb coordination is more impaired than previously thought in persons with PD, though the mechanisms underlying these changes in persons with PD remain somewhat unclear. Further, this study provides support for the use of continuous measures when analyzing interlimb coordination in future research. These findings may also indicate that neurological mechanisms which couple the swing of the arms and legs are disrupted in PD and further suggest that movement of the arms should be considered in gait rehabilitation in persons with PD.

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References

- Baltadjieva R, Giladi N, Gruendlinger L, Peretz C, Hausdorff JM. Marked alterations in the gait timing and rhythmicity of patients with de novo Parkinson's disease. *Eur J Neurosci*. 2006; 24(6):1815–20. [PubMed: 17004944]
- Blin O, Ferrandez AM, Serratrice G. Quantitative analysis of gait in Parkinson patients: increased variability of stride length. *J Neurol Sci*. 1990; 98(1):91–97. [PubMed: 2230833]
- Bruijn SM, Meijer OG, Beek PJ, van Dieën JH. The effects of arm swing on human gait stability. *J Exp Biol*. 2010; 213(23):3945–52. [PubMed: 21075935]
- Carpinella I, Crenna P, Rabuffetti M, Ferrarin M. Coordination between upper- and lower-limb movements is different during overground and treadmill walking. *Eur J Appl Physiol*. 2010; 108(1):71–82. [PubMed: 19756711]
- Collins SH, Adamczyk PG, Kuo AD. Dynamic arm swinging in human walking. *Proc Biol Sci*. 2009; 276(1673):3679–88. [PubMed: 19640879]
- Crenna P, Carpinella I, Lopiano L, Marzegan A, Rabuffetti M, Rizzone M, et al. Influence of basal ganglia on upper limb locomotor synergies. Evidence from deep brain stimulation and L-DOPA treatment in Parkinson's disease. *Brain*. 2008; 131(Pt 12):3410–20. [PubMed: 18952669]
- Dietz V, Michel J. Locomotion in Parkinson's disease: neuronal coupling of upper and lower limbs. *Brain*. 2008; 131(Pt 12):3421–31. [PubMed: 18930965]
- Donker SF, Beek PJ, Wagenaar RC, Mulder T. Coordination between arm and leg movements during locomotion. *J Mot Behav*. 2001; 33(1):86–102. [PubMed: 11303522]
- Eftman H. The function of the arms in walking. *Hum Biol*. 1939; 11:529–35.
- Hinrichs RN, Cavanaugh PR. Upper extremity function during treadmill walking. *Med Sci Sports Exerc*. 1981; 13:96.
- Huang X, Mahoney JM, Lewis MM, Guangwei D, Piazza SJ, Cusumano JP. Both coordination and symmetry of arm swing are reduced in Parkinson's disease. *Gait Posture*. 2012; 35(3):373–7. [PubMed: 22098825]
- Jahn K, Deutschländer A, Stephan T, Kalla R, Hüfner K, Wagner J, et al. Supraspinal locomotor control in quadrupeds and humans. *Prog Brain Res*. 2008; 171:353–62. [PubMed: 18718326]
- Kadaba MP, Ramakrishnan HK, Wooten ME. Lower extremity kinematics during level walking. *J Orthop Res*. 1990; 8:849–60.
- Krasovsky T, Baniña MC, Hacmon R, Feldman AG, Lamontagne A, Levin MF. Stability of gait and interlimb coordination in older adults. *J Neurophysiol*. 2012; 107(9):2560–9. [PubMed: 22298827]
- Krasovsky T, Levin MF. Review: Toward a better understanding of coordination in healthy and poststroke gait. *Neurorehabil Neural Repair*. 2010; 24(3):213–24. [PubMed: 19822722]
- Kwakkel G, Wagenaar RC. Effect of duration of upper- and lower-extremity rehabilitation sessions and walking speed on recovery of interlimb coordination in hemiplegic gait. *Physical Therapy*. 2002; 82:432–48. [PubMed: 11991797]

- Lewek MD, Poole R, Johnson J, Halawa O, Huang X. Arm swing magnitude and asymmetry during gait in the early stages of Parkinson's disease. *Gait Posture*. 2010; 31(2):256–60. [PubMed: 19945285]
- Meyns P, Van Gestel L, Bruijn SM, Desloovere K, Swinnen SP, Duysens J. Is interlimb coordination during walking preserved in children with cerebral palsy? *Res Dev Disabil*. 2012; 33(5):1418–28. [PubMed: 22522200]
- Nanhoe-Mahabier W, Snijders AH, Delval A, Weerdesteyn V, Duysens J, Overeem S, Bloem BR. Walking patterns in Parkinson's disease with and without freezing of gait. *Neuroscience*. 2011; 182:217–24. [PubMed: 21382449]
- Orfanidis, SJ. An Introduction. 2. Vol. 6. Prentice-Hall; Englewood Cliffs, NJ: 1996. Optimum Signal Processing; p. 272
- Park J. Synthesis of natural arm swing motion in human bipedal walking. *J Biomech*. 2008; 41(7):1417–26. [PubMed: 18417138]
- Park K, Dankowicz H, Hsiao-Weckler ET. Characterization of spatiotemporally complex gait patterns using cross-correlation signatures. *Gait Posture*. 2012; 36(1):120–6. [PubMed: 22390962]
- Pickering RM, Grimbergen YA, Rigney U, Ashburn A, Mazibrada G, Wood B, et al. A meta-analysis of six prospective studies of falling in Parkinson's disease. *Mov Disord*. 2007; 22(13):1892–1900. [PubMed: 17588236]
- Pierantozzi M, Palmieri MG, Galati S, Stanzione P, Peppe A, Tropepi D, et al. Pedunculopontine nucleus deep brain stimulation changes spinal cord excitability in Parkinson's disease patients. *J Neural Transm*. 2008; 115(5):731–35. [PubMed: 18196202]
- Riley PO, Paolini G, Della Croce U, Paylo KW, Kerrigan DC. A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. *Gait Posture*. 2007; 26(1):17–24. [PubMed: 16905322]
- Van Emmerik RE, Wagenaar RC. Dynamic movement coordination and tremor during gait in Parkinson's disease. *Hum Mov Sci*. 1996; 15(2):203–35.
- Van Emmerik RE, Wagenaar RC, Winogrodzka A, Wolters EC. Identification of axial rigidity during locomotion in Parkinson disease. *Arch Phys Med Rehabil*. 1999; 80(2):186–91. [PubMed: 10025495]
- Wagenaar RC, van Emmerik RE. Resonant frequencies of arms and legs identify different walking patterns. *J Biomech*. 2000; 33(7):853–61. [PubMed: 10831760]
- Winogrodzka A, Wagenaar RC, Booij J, Wolters EC. Rigidity and bradykinesia reduce interlimb coordination in Parkinsonian gait. *Arch Phys Med Rehabil*. 2005; 86(2):183–9. [PubMed: 15706541]
- Wood BH, Binterlimbcoordinationlough JA, Bowron A, Walker RW. Incidence and prediction of falls in Parkinson's disease: a prospective multidisciplinary study. *J Neurol Neurosurg Psychiatry*. 2002; 72(6):721–5. [PubMed: 12023412]
- Yogev G, Plotnik M, Peretz C, Giladi N, Hausdorff JM. Gait asymmetry in patients with Parkinson's disease and elderly fallers: when does the bilateral coordination of gait require attention? *Exp Brain Res*. 2007; 177(3):336–46. [PubMed: 16972073]
- Zehr EP, Duysens J. Regulation of arm and leg movement during human locomotion. *Neuroscientist*. 2004; 10(4):347–61. [PubMed: 15271262]

Figure 1.

Range of motion (ROM) of the hip (left) and shoulder (right) in healthy older adults (HOA) and persons with PD. LA indicates the less affected side in the persons with PD and MA indicates the more affected side. * indicates $p < .05$.

Figure 2.

Measures of ipsilateral (left) and contralateral (right) interlimb coordination in healthy older adults (controls) and persons with PD. LA indicates the less affected side in the persons with PD and MA indicates the more affected side. * indicates $p < .05$.