2009

A kinematic and electromyographic analysis of turning in people with Parkinson disease

Minna Hong
Washington University School of Medicine in St. Louis

Joel S. Perlmutter
Washington University School of Medicine in St. Louis

Gammon M. Earhart
Washington University School of Medicine in St. Louis

A Kinematic and Electromyographic Analysis of Turning in People With Parkinson Disease

Minna Hong[1,2,3], Joel S. Perlmutter[1,2,3,4,5], Gammon M. Earhart[1,2,3,4]

1 Movement Science Program
2 Program in Physical Therapy
3 Neurology
4 Anatomy and Neurobiology
5 Radiology, Washington University School of Medicine, St. Louis, MO 63108

Running Head: Turning in Controls and PD
Number of Pages: 22
Number of Figures: 8
Number of Tables: 3
Text: 3758 words
Abstract: 246 words

Corresponding Author:
Gammon M. Earhart, PhD, PT
Washington University
School of Medicine
Program in Physical Therapy
4444 Forest Park Blvd.
Campus Box 8502
St. Louis, MO 63108
(314) 286-1425
(314) 286-1410 (FAX)
email: earhartg@msnotes.wustl.edu

ABSTRACT

Background. Parkinson disease (PD) frequently causes difficulty turning that can lead to falls, loss of independence and diminished quality of life. Turning in tight spaces, which may be particularly impaired in PD, is an essential part of our daily lives, yet a comprehensive analysis of in-place turning has not been published. *Objective*. The purpose of this study was to determine whether there are objective differences in turning between people with PD and unimpaired people. *Methods.* We characterized turning in-place with kinematics and electromyographic (EMG) measures in 11 subjects with PD and 12 healthy people. We recorded kinematic data using a 3-D motion capture system in synchrony with EMG data from lower extremity muscles as participants turned 180 degrees. Those with PD were tested after overnight withdrawal of medication. *Results.* Both groups used two distinct turning strategies. In one, the foot ipsilateral to the turning direction initiated the turn and in the other, the foot contralateral to the turning direction initiated the turn. Kinematic analysis demonstrated a cranio-caudal sequence of turning in the unimpaired group, whereas those with PD had a simultaneous onset of yaw rotation of the head, trunk, and pelvis. Thoses with PD also took longer time and more steps to complete turns. Overall lower extremity muscle activation patterns appeared similar between groups. *Conclusion.* Differences between the groups were noted for axial control but lower extremity muscle patterns were similar. This work provides the foundation for development of new treatments for difficulty turning in PD.

Keywords: turning, Parkinson disease, EMG, kinematics

INTRODUCTION

A high percentage (52-62%) of patients with PD report turning difficulties[1-3] that are associated with increased risk for falls.[1,2,4-7] Turning difficulties in people with PD are also associated with freezing, a sudden interruption of ongoing movement.[4,8-10] Given that: 1) people with PD have a nine-fold increased risk of sustaining recurrent falls than unimpaired people, 2) average survival is reduced to approximately 7 years once recurrent falls are present[11], 3) people with PD are 3.2 times more susceptible to hip fractures than those without PD[12], 4) falls during turning are eight times more likely to result in hip fractures compared to falls during straight-line walking[13], 5) 25% of patients with PD develop a hip fracture within 10 years of being diagnosed[14] and 6) healthcare cost to treat hip fractures in PD are reaching $ 192 million per year[12,15], more efforts need to be made to better understand normal and abnormal patterns of turning so we can address turning difficulties in PD.

Healthy young and older people engage a cranio-caudal sequence of movements to turn while walking, with head rotation leading trunk then pelvis rotation in the yaw plane to reorient the body towards a new direction.[16,17] The specific patterns of muscle activation that underlie turning remain unclear with only a single study reporting subtle modifications of muscle activation patterns during turning compared to straight walking.[18]

Several studies of people with PD have examined kinematics of turning during walking[19-21], turning in-place, or turning during everyday tasks.[3,22] People with PD lack the normal cranio-caudal turning sequence with decreased intersegmental movement that produces the “en bloc” turn.[19,20] People with PD also lack heel strike[3,22], have lower

trunk angular velocities[21], take longer to turn[21], have a narrower base of support[19], and take more steps compared to unimpaired people.[3,19,20] No study has examined muscle activity patterns associated with turning in PD and the studies described previously all evaluated participants when "on" medication. Controlling the effect of medication is crucial since medication can mask disease symptoms. Observations made with subjects on medications are thus confounded, as it is not clear whether observed effects or lack of effects is attributable to the disease process, to medications, or to a combination of the two.In addition, testing on medications introduced unwanted variability because each individual takes different medications in different combinations and different dosages. The purpose of this study was to examine, using kinematics and electromyography (EMG), in-place turning in people with PD evaluated off medications compared to unimpaired people.

METHODS

Subjects

We recruited 12 unimpaired people (mean age $\pm$ SD; 72 $\pm$10 years) and 11 people diagnosed with PD (67 $\pm$7 years) with standard clinical criteria[23] from the Movement Disorders Center at Washington University School of Medicine. People with PD were all recruited from the Center to ensure they were accurately diagnosed with idiopathic PD. The first twelve people with PD that agreed to participate over the telephone were brought in for testing. People with PD were tested after overnight withdrawal of PD medications. Table 1 lists demographic details for the PD group. The Hoehn & Yahr scale[24] rates the patients on a scale of 0 to 5 with higher scores representing more

substantial disease. The patients that participated in the study were Hoehn & Yahr stages II and III, indicating that they were mildly to moderately impaired. The UPDRS subscale III motor rating consists of 14 items and has a maximum score of 56 with higher scores indicating more impaired motor function. All unimpaired people were screened for history or symptoms of neurological diseases. Participants provided written informed consent, and these studies were approved by the Human Research Protection Office at Washington University School of Medicine (protocol 04-0716).

Protocol

Hoehn & Yahr and UPDRS subscale III motor ratings were performed on all people with PD at the beginning of the study. Each person stood in the middle of the room and was instructed to turn 180 degrees to the left and to the right, five times in each direction, in random order. Turns of 180 degrees were selected because they are used in everyday activities and can be consistently elicited from participants without providing an external cue to indicate desired turn amplitude. (Unpublished pilot work from our laboratory examining turns of different amplitudes ranging from 45 to 180 degrees suggested that many people with and without PD do not estimate turn amplitudes well but could consistently produce turns of 180 degrees.) The instructions given were "turn and face the wall behind you whenever you are ready". No instructions were given as to how to turn or which foot to move first. They were asked to turn five times for each direction so that we could average across trials to obtain representative data for each person. The randomization of turn direction was employed to prevent participants from being able to predict turn direction from one trial to the next. We used an eight camera 3-D motion

capture system (Motion Analysis Corporation, Santa Rosa, CA) to record kinematic data. Thirty-three reflective markers were placed on each participant; four on the head (top of the head, left ear, right ear and head offset), five on the trunk (left and right acromions, right scapula, 12th vertebra of the thorax and sternal notch), four on the pelvis (left and right anterior superior iliac spines, left posterior superior iliac spine and sacrum) and ten on each leg (greater trochanter, anterior thigh, femoral condyle, fibular head, middle tibia, lateral malleolus, calcaneus, navicular, 5th metatarsal head and the great toe). Surface EMG data were recorded using a telemetered system (Konigsberg Instruments, Inc., Pasadena, CA). We recorded bilaterally from muscles of the lower extremities (tibialis anterior (Tib), medial head of gastrocnemius (Gas), biceps femoris (Ham), vastus lateralis (Quad), tensor fascia lata (TFL), and gluteus maximus (Glut)) using bipolar surface electrodes. The margin of error for the 3-D motion capture system is within 1 mm and the EMG data were collected using the 3-D motion capture system and werepreciselysynchronized to ensure minimal and consistent timing error (less than 10 ms) with respect to movement. Kinematic and EMG data were synchronously sampled at 100 Hz and 1000 Hz, respectively.

Analysis

The key independent variables of interests were yaw rotation onset times for the head, trunk, and pelvis as well as the amplitudes of relative yaw rotation angles between the different segments and EMG onset times. The independent variables were group (PD vs. unimpaired) and turn strategy (matched and unmatched).

Since people took different number of steps to perform the tasks, only data from the first stride were analyzed to ensure comparison of equivalent regions of the turns. All onset and offset times were expressed as a percentage of the gait cycle allowing normalization of the data without having to control for speed of turning and thereby alterting natural performance of the task. This was our method of choice, as it has been reported that turning speed does not alter turn kinematics.[25] DataPac 2K2 (Run Technologies, Mission Viejo, CA) was used to identify turn onsets. All signals were digitally low-pass filtered at 20Hz (4^{th} order, zero-lag Butterworth filter). Turn onsets were automatically identified using the vertical coordinate of the toe markers via a threshold criterion method. After placing an event at a threshold of 10 mm, the first derivative of the toe marker in the vertical coordinate was determined and the onset event repositioned to the time just prior to the threshold when the rate of change increased from zero. Each marked onset was visually confirmed. Kintrak (Motion Analysis Corporation, Santa Rosa, CA) was used for kinematic analysis to determine: 1) yaw rotation onset times of the head, trunk and pelvis, normalized to the first stride 2) absolute amplitude of angular rotation for each segment in the yaw plane, and 3) amplitude of relative rotation angles between the different segments. EMG signals were root mean square averaged with a time constant of 10 ms in DataPac 2K2. Burst onsets and offsets were defined at a threshold of three standard deviations above baseline and were visually confirmed. Bursts that began up to 500 ms prior to turn onset were included in the analysis. All burst onsets and offsets were normalized to the first stride of the turn.

SigmaStat (Systat Software Inc, Richmond, CA) was used to perform all statistical tests. Two-way ANOVAs were performed for all data that were normally

distributed and Mann-Whitney Rank Sum tests for data that were not normally distributed in testing for differences. Therefore, to test for differences between groups in yaw rotation onset times of the head, trunk and pelvis, we used a two-way ANOVA. Two-way ANOVAs were also used to test for differences between groups in amplitude of absolute yaw rotation angle during the first stride for different segments as well as amplitudes of relative rotation angles between different segments. We performed two-way ANOVAs to test for differences in onset and offset times of different muscles among four different turning strategies within groups. As there were no significant differences within a strategy for turns to the right vs. the left, we were able to lump turns of different directions but same strategy. This reduced the number of overall strategies from four to two. Then we tested for differences in onset and offset times of different muscles between groups, within a turning strategy, using two-way ANOVAs. Mann-Whitney Rank Sum tests were used to test for differences in turn duration and number of steps it took to turn between the two groups. Level of significance was set at $p \leq 0.05$ for all tests.

Power Analysis

Power analyses were conducted using a modest effect size of 0.4, which would allow us to detect a 10% difference between groups. Analyses conducted for yaw rotation onset times indicated a power of 0.85 to detect a main effect of group, 0.83 to detect a main effect of segment, and 0.76 to detect an interaction of group with segment given 11 subjects per group. Analyses conducted for EMG onset times indicated a power

of 0.95 to detect a main effect of group, 0.84 to detect a main effect of muscle, and 0.77 to detect a group by muscle interaction given 11 subjects per group.

RESULTS

Prevalence of different turning strategies

Four different strategies were noted when executing a 180 degree turn: 1) leftward turns starting with the left foot (L start L), 2) rightward turns starting with the right foot (R start R), 3) leftward turns starting with the right foot (L start R), and 4) rightward turns starting with the left foot (R start L). From here on, we will refer to the former two strategies collectively as the "Matched Strategy" and the latter two as the "Unmatched Strategy." The distributions of strategies were almost identical for the PD and unimpaired groups (Figure 1).

There were no differences in kinematic measures between the Matched and Unmatched Strategies, so kinematic data from all strategies were lumped for further analysis. There were differences in EMG patterns between the Matched and Unmatched Strategies, so EMG data were analyzed separately for the two distinct strategies.

Yaw rotation onset kinematics

Figure 2 shows kinematic plots of transverse plane angles in the lab coordinate system for different segments for an unimpaired person (A) and a person with PD (B) as they turned 180 degrees. In the unimpaired person the cranio-caudal sequence of movement is evident, whereas in the person with PD, it is difficult to distinguish the order in which the different segments started turning. These plots also reveal that the

person with PD took more steps and much longer time to complete the turn. The normalized onsets of yaw plane rotation of the head, trunk and pelvis were significantly different between the groups ($p=0.05$, Figure 3). In the unimpaired group, head onset was significantly earlier than the pelvis onset ($p<0.05$). Although we did not find statistically significant differences between head and trunk onsets or between trunk and pelvis onsets, the group means reflect the top down, sequential order in the control but not the PD group. In the PD group, comparison of all three segments did not reveal any significant differences.

Amplitude of yaw rotation angles

The amplitude of yaw rotation at the head, trunk, pelvis, and foot were significantly different between the two groups ($p<0.001$) (Figure 4). The group with PD also demonstrated a tendency to rotate less intersegmentally (Table 2). Head rotation relative to pelvis was statistically different between the two groups ($p=0.027$).

Turn duration and number of steps to turn

The time and number of steps people took to complete the turns were significantly different between the two groups ($p=0.001$ and $p<0.001$, respectively). The PD group required more than twice as long and more than twice the number of steps to execute 180 degree turns (Table 3).

Muscle activation patterns in the unimpaired group

Figure 5 illustrates rectified EMG data when turning to the right for a single person. Figure 5A exemplifies muscle activity patterns during a R start R turn and 5B exemplifies a R start L turn. Figure 6 illustrates all four turning strategies, normalized to the first stride, in the unimpaired group. Visual inspection reveals that the L start L (6A) and R start R (6C) turns look alike and the L start R (6B) and R start L (6D) turns are also similar. As expected, there were no statistical differences in muscle activation patterns between the two similar strategies. Therefore, we collapsed the two Matched Strategies (L start L and R start R strategies) as well as the Unmatched Strategies (L start R and R start L strategies).

Matched Strategies were characterized by early bursts in contralateral gluteus maximus, tensor fascia lata, vastus lateralis and gastrocnemius as well as ipsilateral biceps femoris and tibialis anterior. These same muscles had a second burst later in the cycle. There were mid-cycle bursts in contralateral biceps femoris and tibialis anterior as well as ipsilateral gluteus maximus, tensor fascia lata, vastus lateralis, and gastrocnemius. These muscles displayed only a single burst in the gait cycle.

Like the Matched Strategies, Unmatched Strategies were characterized by early bursts in contralateral tensor fascia lata, vastus lateralis, and gastrocnemius as well as ipsilateral tibialis anterior. These same muscles had a second burst later in the cycle. Also like the Matched Strategy, there were mid-cycle bursts in contralateral biceps femoris and tibialis anterior as well as ipsilateral gluteus maximus, tensor fascia lata, vastus lateralis, and gastrocnemius. In addition, there was a mid-cycle burst in the ipsilateral biceps femoris. The most apparent difference between the Matched and Unmatched strategies was that the contralateral gluteus maximus and ipsilateral biceps

femoris muscles had two bursts in the Matched Strategy and only one burst in the Unmatched Strategy.

Muscle activation patterns in PD

Figure 7A exemplifies rectified EMG patterns during a L start L turn and 7B exemplifies a L start R turn for a person with PD. As was the case in the unimpaired group, we did not find any statistical differences in muscle activation patterns between the two Matched Strategies and the two Unmatched Strategies in the PD group. Therefore, we again combined the two similar strategies. Figure 8 illustrates normalized EMG patterns for the Matched (A, C) and Unmatched Strategies (B, D) for the unimpaired and the PD groups. In these figures, the ipsilateral (I) muscles correspond to the muscles on the same side as the starting foot, regardless of the type of strategy used, and contralateral (C) muscles to the other side. Statistical tests revealed no significant differences between the groups for the Matched Strategy. However, for the Unmatched Strategy the onset times for the first burst of the contralateral tibialis anterior ($p<0.001$), contralateral biceps femoris ($p=0.03$), and ipsilateral biceps femoris ($p<0.001$) as well as the offset times for the contralateral tibialis anterior ($p=0.002$), ipsilateral tibialis anterior ($p=0.045$), and ipsilateral tensor fascia lata ($p=0.002$) were significantly different between the PD and unimpaired groups. Compared to the unimpaired group, the contralateral tibialis anterior was activated earlier and deactivated earlier, the ipsilateral tibialis anterior deactivated earlier, the contralateral biceps femoris activated later, the ipsilateral biceps femoris activated earlier, and the ipsilateral tensor fascia lata had longer sustained activity in the PD group.

DISCUSSION

This investigation examined in-place 180 degree turns in healthy unimpaired people and people with PD to quantify the turning strategies used by each group. While differences between the groups were noted for axial control, lower extremity patterns were similar.

Turning strategies

Both groups demonstrated two different turning strategies. People either started with the foot ipsilateral to the turning direction (Matched) or with the opposite foot (Unmatched). Although we anticipated that most people would start turning with the ipsilateral foot (Matched), both groups were slightly more likely to employ the Unmatched Strategy than the Matched. Our results agree with those of Meinhart-Shibata et al.[26] who reported that older women used the Unmatched Strategy 65% of the time when turning. They suggested that the Unmatched Strategy provided a precautionary strategy for turning that was safer due to reduced angle of lower extremity external rotation required for subsequent steps, producing a larger anterior/posterior dimension of the base of support compared to the Matched Strategy. Both groups used the same proportions of each strategy suggesting that the presence of the Unmatched Strategy may be an effect of aging. If it were a precautionary strategy, we would expect to observe it more in the group with PD and less in the unimpaired group. As this was not observed, we speculate that it may be a natural phenomenon to use both Matched and Unmatched Strategies interchangeably, just as one can initiate walking with the right or the left foot.

Kinematic analysis

Our results on yaw rotation onset of the head, trunk and pelvis reflect the cranio-caudal sequence of turning in the unimpaired group but not the PD group. These findings agree with other studies of unimpaired people[16,17] and people with PD.[20] People with PD also rotated less at the head, trunk, pelvis, and foot during the first stride of the turns. This was associated with longer time to turn and more steps to complete the turns than the unimpaired group. Other investigators have reported similar findings.[19-21] Finally, we noted decreased relative rotation between segments during turning in the PD group. To our knowledge, this is the first quantification of en bloc turning in PD.

EMG analysis

This is the first study to demonstrate muscle activation patterns in the lower extremities during in-place 180 degree turns in unimpaired and people with PD. When comparing across turning strategies, the Matched Strategy produced two bursts in the ipsilateral biceps femoris and contralateral gluteus maximus muscles and the Unmatched strategy produced only one burst in each. Both of these extra bursts were near the beginning of the turn, possibly indicating that the Matched Strategy is indeed more difficult than the Unmatched and requires more stabilization via cocontraction to take the first step of the turn.

The overall EMG patterns for the two groups were generally similar within turning strategies. One feature of note is the increased variability in the PD group, a feature known to be associated with medication withdrawal.[19] Between-group differences

in a few muscle onsets (the first burst of the contralateral tibialis anterior, contralateral biceps femoris, and ipsilateral biceps femoris) and offsets (the contralateral tibialis anterior, ipsilateral tibialis anterior, and ipsilateral tensor fascia lata) were only present in the Unmatched Strategy and not in the Matched.

Despite the overall similarities of lower extremity EMG patterns between the two groups, kinematic data from the axial segments appear quite different. This is in line with earlier reports of Morris et al., suggesting that PD affects the ability to scale movements but basic movement forms remain intact.[27] Our results suggest that turning difficulties in PD stem primarily from deficits in axial control, leaving the lower extremities relatively unaffected, at least at the moderate stage of the disease examined in this study. We did not collect EMG data from axial muscles, and axial rigidity may be a contributing factor to turning difficulties in PD.[28,29] Nagumo and Hirayama[28] reported that people with PD exhibited continuous electrical activity in axial muscles when the trunk was passively rotated, a finding not present in unimpaired people. EMG data from axial musculature may have revealed differences between the two groups and should be included in future studies.

We describe basic kinematic and muscle activation patterns associated with in-place 180 degree turning in unimpaired and in people with PD. This is an important task to examine because people with PD most commonly fall in familiar settings, like their homes, while engaging in everyday household chores.[7] A minimum of two turns per 10 steps are required to carry out common daily activities.[30] Examples of performing 180 degree turns include entering a public restroom stall and having to turn around before sitting down or taking something out of a refrigerator and turning to place it on the

counter directly opposite. In addition to its functional relevance, the task of turning in-place lends itself well to use in the laboratory. Turning in-place can be readily assessed, as in-place turns have a clear beginning and end in contrast to turns made during walking. Turns of 180 degrees in particular can also be consistently produced from trial to trial without the need for external cues to signal desired turn amplitude. Quantification of turning in-place may provide a biomarker of risk of falling and as such could provide a key link from a laboratory-based measure to an important clinical endpoint. Of course, this link remains to be substantiated. The data obtained from this investigation also may provide the basis for further evaluation of mechanisms of turning that can help devise appropriate adaptive strategies to alleviate functional disabilities in real-life situations. Examples may include maneuvering an object in the hands or having a conversation while performing in-place turning. Previous research has shown that dual tasking adversely affects motor performance in people with PD.[31-35] Such tasks may accentuate turning difficulties and allow us to definitively identify which factors contribute to turning difficulties in people with PD.

ACKNOWLEDGMENTS

We thank Joshua Funk, Michael Falvo, Karen Stringer and Callie Mosiman for their assistance in data analysis. This work was supported by NIH grants 1 K01 HD048437, NS41509, 1 F31 NS056653, PODS II from the Foundation for Physical Therapy, the Greater St. Louis Chapter of the American Parkinson Disease Association (APDA), the APDA Center for Advanced PD Research at Washington University and the Barnes-Jewish Hospital Foundation (the Elliot H. Stein Family Fund and the Jack Buck Fund for PD Research).

REFERENCES

1. Nieuwboer A, De Weerdt W, Dom R, Lesaffre E. A frequency and correlation analysis of motor deficits in Parkinson patients. *Disabil Rehabil*. 1998;20(4):142-50.
2. Bloem BR, Grimbergen YA, Cramer M, Willemsen M, Zwinderman AH. Prospective assessment of falls in Parkinson's disease. *J Neurol*. 2001;248(11):950-8.
3. Stack EL, Ashburn AM, Jupp KE. Strategies used by people with Parkinson's disease who report difficulty turning. *Parkinsonism Relat Disord*. 2006;12(2):87-92.
4. Giladi N, McMahon D, Przedborski S. Motor blocks in Parkinson's disease. *Neurology*. 1992;42:333–339.
5. Charlett A, Weller C, Purkiss A, Dobbs S, Dobbs R. Breadth of base whilst walking: effect of ageing and parkinsonism. *Age Ageing.* 1998;27:48-54.
6. Bloem B, Van Vugt J, Beckley D. Postural instability and falls in Parkinson's disease. *Adv. Neurol*. 2001;87:209-223.
7. Stack E, Ashburn A. Fall-events described by people with Parkinson's disease: implication for clinical interviewing and the research agenda. *Physiother*. 1999;4:190-200.
8. Lamberti P, Armenise S, Castaldo V et al. Freezing gait in Parkinson's disease. *Eur. Neurol*. 1997;38:297–301.

9. Schaafsma JD, Balash U, Gurevich T, Bartels AL, Hausdorff JM, Giladi N. Characterization of freezing of gait subtypes and the response of each to levodopa in Parkinson's disease. *Eur. J. Neurol.* 2003;10:391–398.
10. Bloem BR, Hausdorff JM, Visser JE, Giladi N. Falls and freezing of gait in Parkinson's disease: a review of two interconnected, episodic phenomena. *Mov. Disord.* 2004;19(8):871–884.
11. Wenning GK, Litvan I, Jankovic J et al. Natural history and survival of 14 patients with corticobasal degeneration confirmed at postmortem examination. *J Neurol Neurosurg Psychiatry*. 1998;64(2):184-9.
12. Melton III LJ, Leibson CL, Achenbach SJ et al. Fracture risk after the diagnosis of Parkinson's disease: influence of concomitant dementia. *Mov Disord.* 2006;21(9):1361-1367.
13. Cumming R, Klineberg R. Fall frequency and characteristics and the risk of hip fractures. *J Am Ger Soc.* 1994;42:774-778.
14. Johnell O, Melton LJ 3rd, Atkinson EJ, O'Fallon WM, Kurland LT. Fracture risk in patients with parkinsonism: a population-based study in Olmsted County, Minnesota. *Age Ageing*. 1992;21(1):32-8.
15. Bacon, WE. Secular trends in hip fracture occurrence and survival rate: age and sex differences. *J Aging Health.* 1996;8:538-53.
16. Patla AE, Adkin A, Ballard T. Online steering: coordination and control of body center of mass, head and body reorientation. *Exp Brain Res*. 1999;129(4):629-34.
17. Fuller JR, Adkin AL, Vallis LA. Strategies used by older adults to change travel direction. *Gait Posture*. 2007;25(3):393-400.

18. Courtine G, Schieppati M. Tuning of a basic coordination pattern constructs straight-ahead and curved walking in humans. *J Neurophysiol*. 2004;91(4):1524-35.

19. Morris ME, Huxham F, McGinley J, Dodd K, Iansek R. The biomechanics and motor control of gait in Parkinson disease. *Clin Biomech* (Bristol, Avon). 2001;16(6):459-70.

20. Crenna P, Carpinella I, Rabuffetti M et al. The association between impaired turning and normal straight walking in Parkinson's disease. *Gait Posture*. 2007;26(2):172-8.

21. Visser JE, Voermans NC, Oude Nijhuis LB et al. Quantification of trunk rotations during turning and walking in Parkinson's disease. *Clin Neurophysiol*. 2007;118(7):1602-6.

22. Stack E, Jupp K, Ashburn A. Developing methods to evaluate how people with Parkinson's Disease turn 180 degrees: an activity frequently associated with falls. *Disabil Rehabil*. 2004;26(8):478-84.

23. Racette BA, Rundle M, Parsian A, Perlmutter JS. Evaluation of a screening questionnaire for genetic studies of Parkinson's disease. *Am J Med Genet*. 1999;88(5): 539-43.

24. Hoehn MM, Yahr MD. Parkinsonism: onset, progression, and mortality. 1967. *Neurology*. 2001;57(10 Suppl 3):S11-26.

25. Lamontagne A, Paquette C, Fung J. Stroke affects the coordination of gaze and posture during preplanned turns while walking. *Neurorehabil Neural Repair.* 2007:62-7.

26. Meinhart-Shibata P, Kramer M, Ashton-Miller JA, Persad C. Kinematic analyses of the 180 degrees standing turn: effects of age on strategies adopted by healthy young and older women. *Gait Posture*. 2005;22(2):119-25.
27. Morris M, Iansek R, McGinley J, Matyas T, Huxham F. Three-dimensional gait biomechanics in Parkinson's disease: evidence for a centrally mediated amplitude regulation disorder. *Mov Disord*. 2005;20(1):40-50.
28. Nagumo K, Hirayama K. A study on truncal rigidity in parkinsonism-evaluation of diagnostic test and electrophysiological study. *Rinsho Shinkeigaku*. 1993;33(1):27-35.
29. Schenkman M, Morey M, Kuchibhatla M. Spinal flexibility and balance control among community-dwelling adults with and without Parkinson's disease. *J Gerontol A Biol Sci Med Sci*. 2000;55(8):M441-5.
30. Sedgman R, Goldie P. Development of a measure of turning during walking. In: *Advancing rehabilitation:Proceedings inaugural congerence of Faculty of Health Sciences*, La Trobe Univeristy, 1994; Melbourne, Australia.
31. Bond JM, Morris M. Goal-directed secondary motor tasks: their effects on gait in subjects with Parkinson disease. *Arch Phys Med Rehabil*. 2000;81(1):110-6.
32. Camicioli R, Oken BS, Sexton G, Kaye JA, Nutt JG. Verbal fluency task affects gait in Parkinson's disease with motor freezing. *J Geriatr Psychiatry Neurol*. 1998;11(4):181-5.
33. O'Shea S, Morris ME, Iansek R. Dual task interference during gait in people with Parkinson disease: effects of motor versus cognitive secondary tasks. *Phys Ther*. 2002;82(9):888-97.

34. Yogev G, Giladi N, Peretz C, Springer S, Simon ES, Hausdorff JM. Dual tasking, gait rhythmicity, and Parkinson's disease: which aspects of gait are attention demanding? *Eur J Neurosci*. 2005;22(5):1248-56.

35. Springer S, Giladi N, Peretz C, Yogev G, Simon ES, Hausdorff JM. Dual-tasking effects on gait variability: the role of aging, falls, and executive function. *Mov Disord*. 2006;21(7):950-7.

Figure legends

Figure 1. Distribution of different turning strategies used for PD and unimpaired groups.

Figure 2. Plots of yaw plane angles in the lab coordinate system, of different segments for an unimpaired person (A) and a person with PD (B) as they performed a 180 degree turn.

Figure 3. Normalized onsets of rotation in the yaw plane of the head, trunk and pelvis for unimpaired and PD groups. Asterisk indicates a statistically significant difference between head onset and pelvis onset in the unimpaired group ($p<0.05$).

Figure 4. Comparison of amplitude of absolute yaw rotation angles for the head, trunk, pelvis, and starting foot for unimpaired and PD groups. Asterisks indicate statistically significant differences between the two group (all $p<0.001$).

Figure 5. Illustration of rectified EMG data for rightward turns in an unimpaired person. (A) exemplifies muscle activity patterns during a R start R turn and (B) exemplifies a R start L turn. The two vertical lines denote the beginning and end of the stride.

Figure 6. Illustration of all four turning strategies, normalized to the first stride, in the unimpaired group.

Figure 7. Illustration of rectified EMG data for leftward turns in a person with PD. (A) exemplifies muscle activity patterns during a L start L turn and (B) exemplifies a L start R turn. The two vertical lines denote the beginning and end of the stride.

Figure 8. Illustration of Matched and Unmatched Strategies for unimpaired and PD group. Muscles are labeled I (ipsilateral) or C (contralateral) relative to the direction of the turns. Asterisks indicate statistically significant differences in onset and offset of muscles between the two groups ($p<0.05$).

TABLE 1: Subject Demographics

Subject	Age	Gender	Time Since PD Diagnosis (years)	UPDRS* Total Motor Subscore Subscore
PD1	76	M	8	46.5
PD2	78	M	2	22.0
PD3	60	M	8	51.0
PD4	68	F	3	21.5
PD5	66	M	8	26.0
PD6	74	M	6	31.5
PD7	57	M	8	39.0
PD8	66	M	4	30.5
PD9	63	M	21	36.5
PD10	71	F	10	48.0
PD11	58	M	6	31.0

*UPDRS scores were obtained with subjects off medications. Items are rated on a scale of 0-4: 0 = absent, 1 = slight, 2 = mild to moderate, 3 = marked, 4 = severe.

Table 2. Average (± SE) yaw rotation angles

	Unimpaired	PD
Head rel. Trunk	14.33 ± 2.08	11.12 ± 1.91
Trunk rel. Pelvis	7.92 ± 1.18	4.41 ± 0.41
Head rel. Pelvis *	18.59 ± 2.25	12.91 ± 1.99

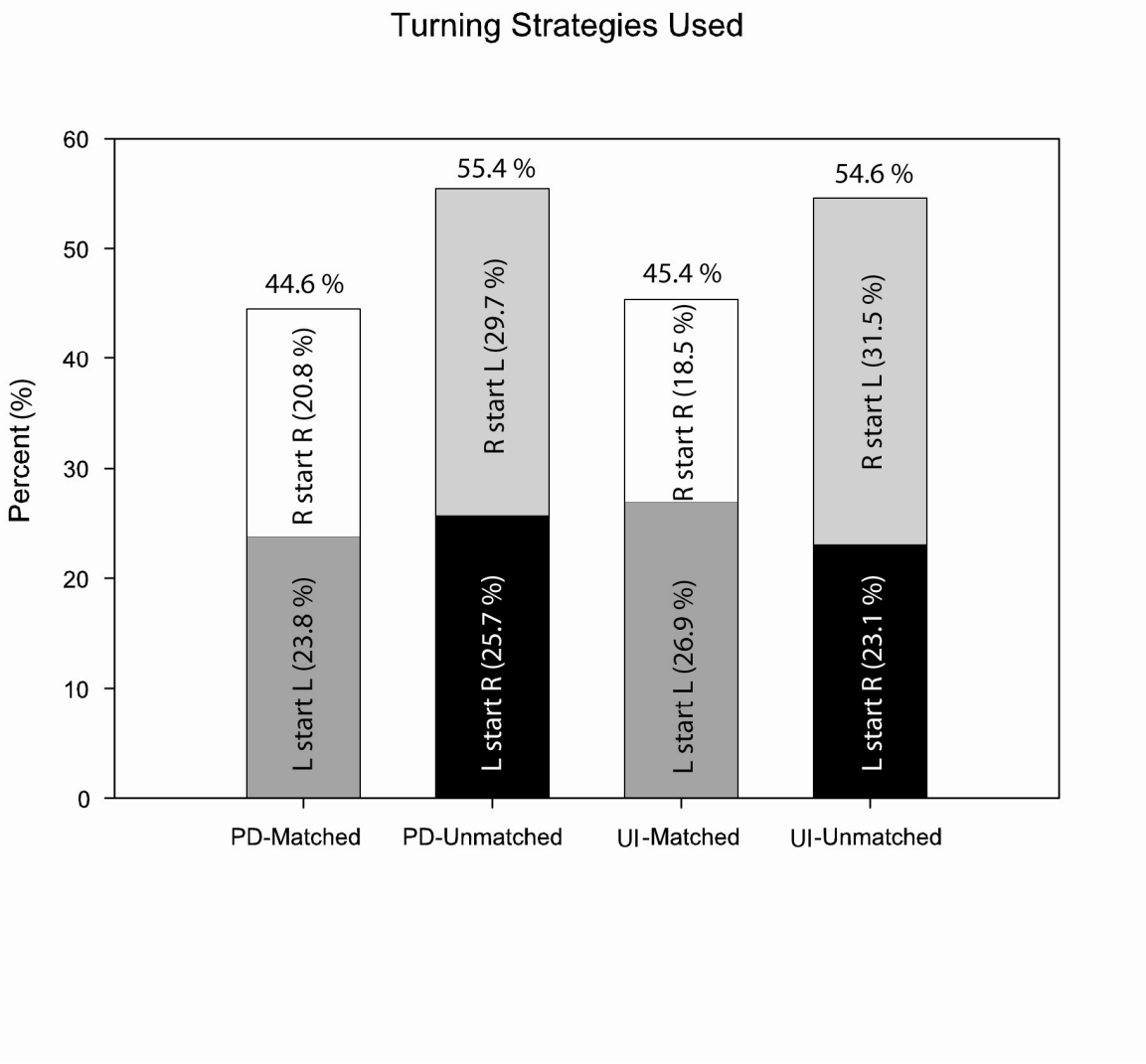
* Significantly different between the groups, p=0.027

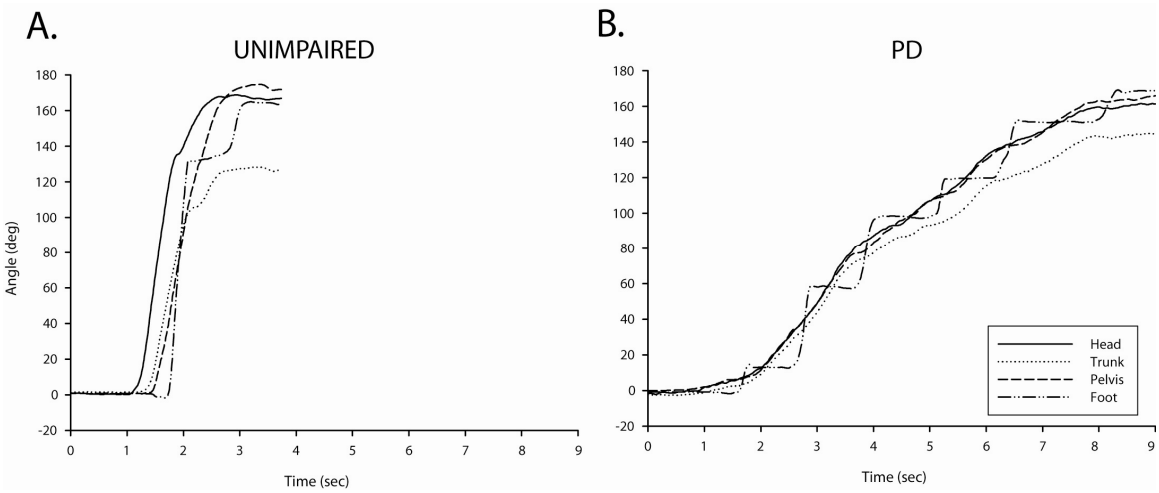
Table 3. Comparison of turning time and steps to turn

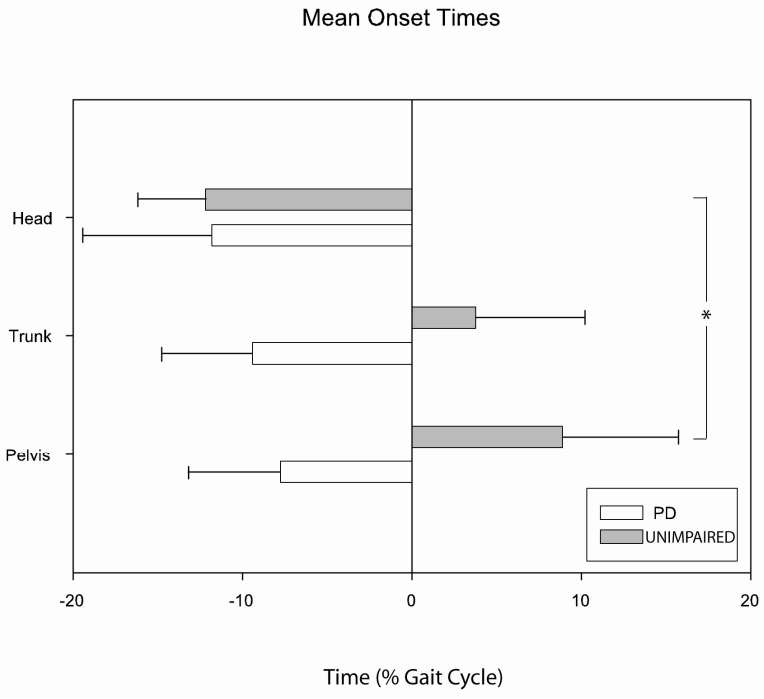
	Unimpaired	PD	p
Turn duration (sec)	3.37 ± 0.26	9.28 ± 2.72	0.001
Number of Steps	5.05 ± 0.29	13.02 ± 2.86	< 0.001

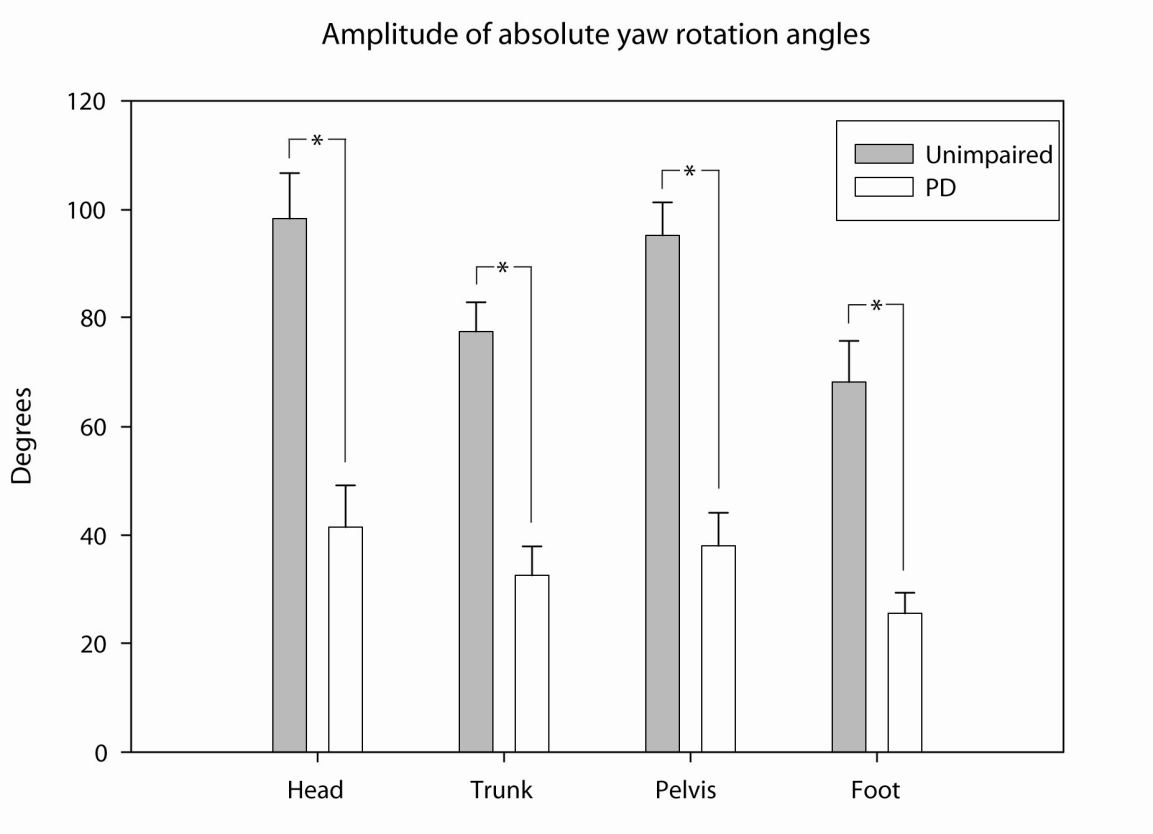
Values reported are means ± SE.

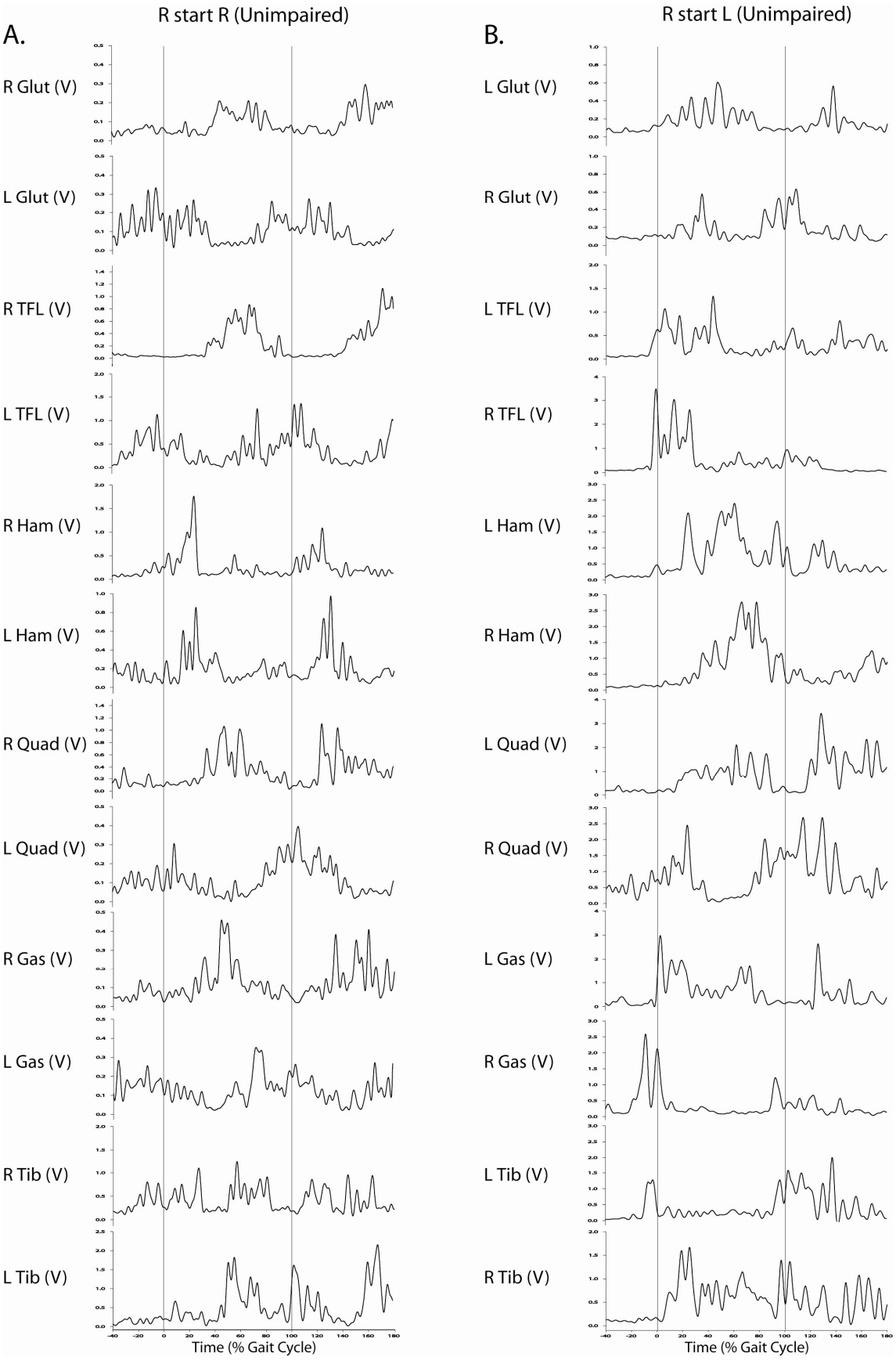
p values are from Mann-Whitney Rank Sum Test comparing unimpaired vs. PD group.


Turning Strategies Used
Percent (%)
60
50
40
30
20
10
0
44.6 %
55.4 %
45.4 %
54.6 %
R start R (20.8 %)
L start L (23.8 %)
R start L (29.7 %)
L start R (25.7 %)
R start R (18.5 %)
L start L (26.9 %)
R start L (31.5 %)
L start R (23.1 %)
PD-Matched
PD-Unmatched
UI-Matched
UI-Unmatched

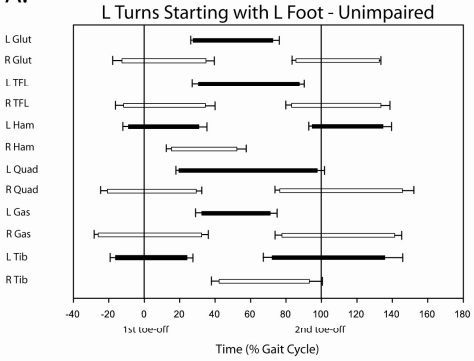

A.
UNIMPAIRED
Angle (deg)
Time (sec)
B.
PD
Time (sec)
Head
Trunk
Pelvis
Foot


Mean Onset Times
Head
Trunk
Pelvis
*
PD
UNIMPAIRED
-20
-10
0
10
20
Time (% Gait Cycle)

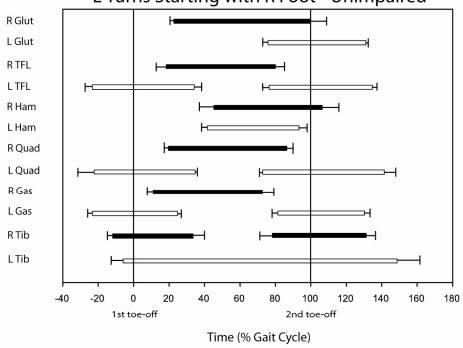

Amplitude of absolute yaw rotation angles
Degrees
120
100
80
60
40
20
0
Unimpaired
PD
*
*
*
*
Head
Trunk
Pelvis
Foot


A.
R start R (Unimpaired)
R Glut (V)
L Glut (V)
R TFL (V)
L TFL (V)
R Ham (V)
L Ham (V)
R Quad (V)
L Quad (V)
R Gas (V)
L Gas (V)
R Tib (V)
L Tib (V)
Time (% Gait Cycle)
B.
R start L (Unimpaired)
L Glut (V)
R Glut (V)
L TFL (V)
R TFL (V)
L Ham (V)
R Ham (V)
L Quad (V)
R Quad (V)
L Gas (V)
R Gas (V)
L Tib (V)
R Tib (V)
Time (% Gait Cycle)

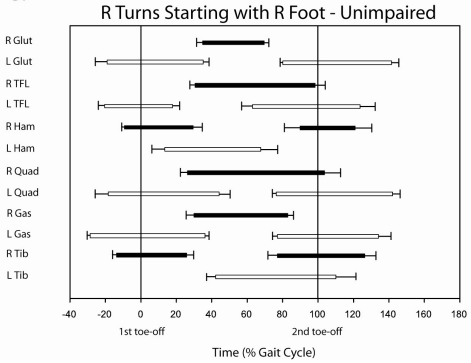
A.


L Turns Starting with L Foot - Unimpaired
L Glut
R Glut
L TFL
R TFL
L Ham
R Ham
L Quad
R Quad
L Gas
R Gas
L Tib
R Tib
-40 -20 0 20 40 60 80 100 120 140 160 180
1st toe-off
2nd toe-off
Time (% Gait Cycle)

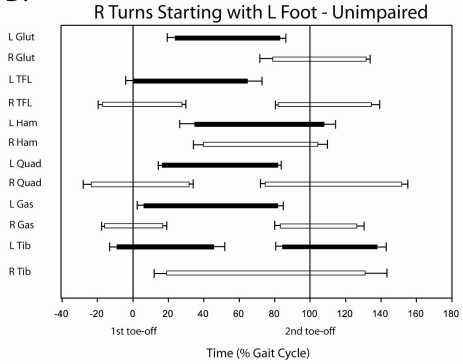
B.

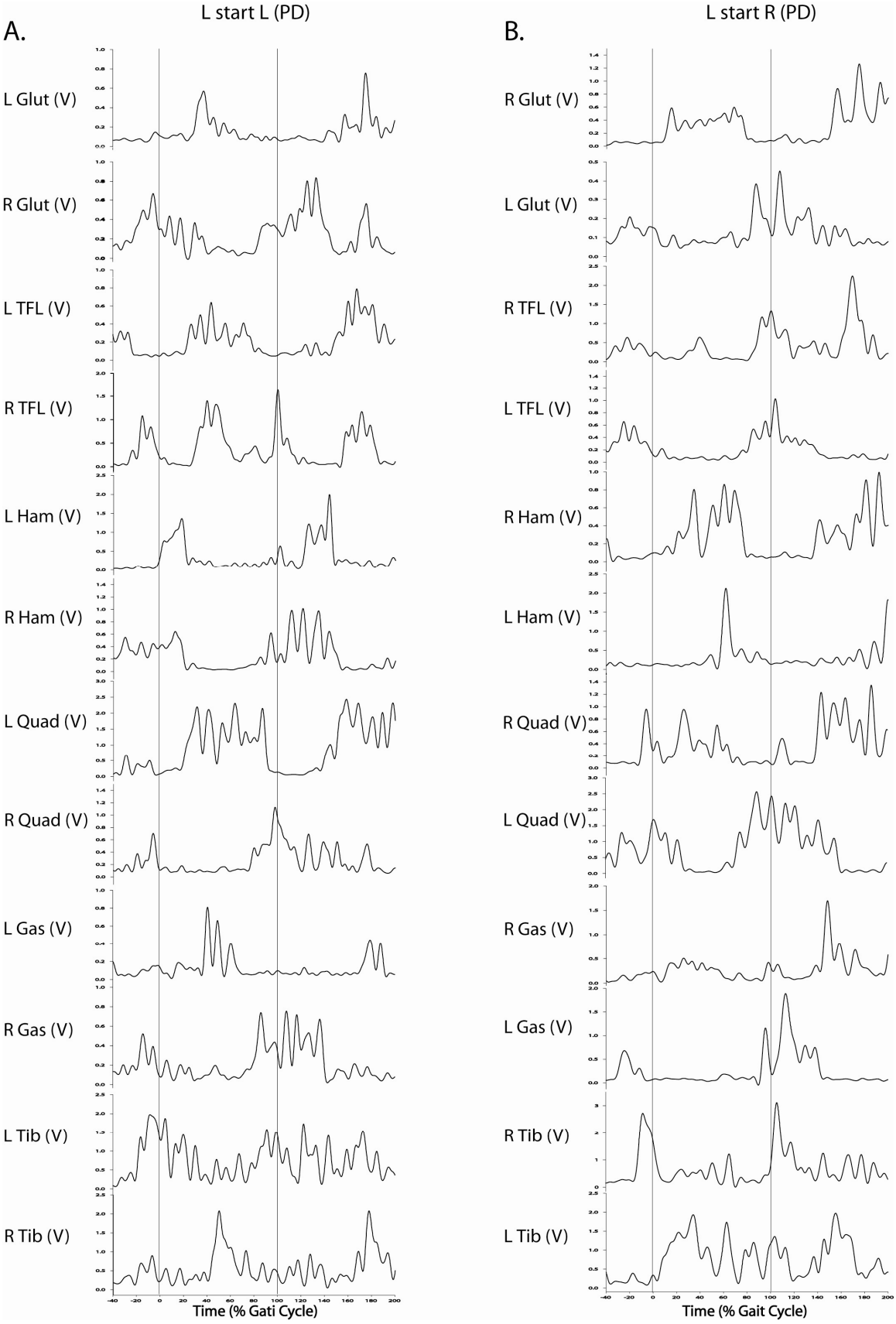

L Turns Starting with R Foot - Unimpaired
R Glut
L Glut
R TFL
L TFL
R Ham
L Ham
R Quad
L Quad
R Gas
L Gas
R Tib
L Tib
-40 -20 0 20 40 60 80 100 120 140 160 180
1st toe-off
2nd toe-off
Time (% Gait Cycle)

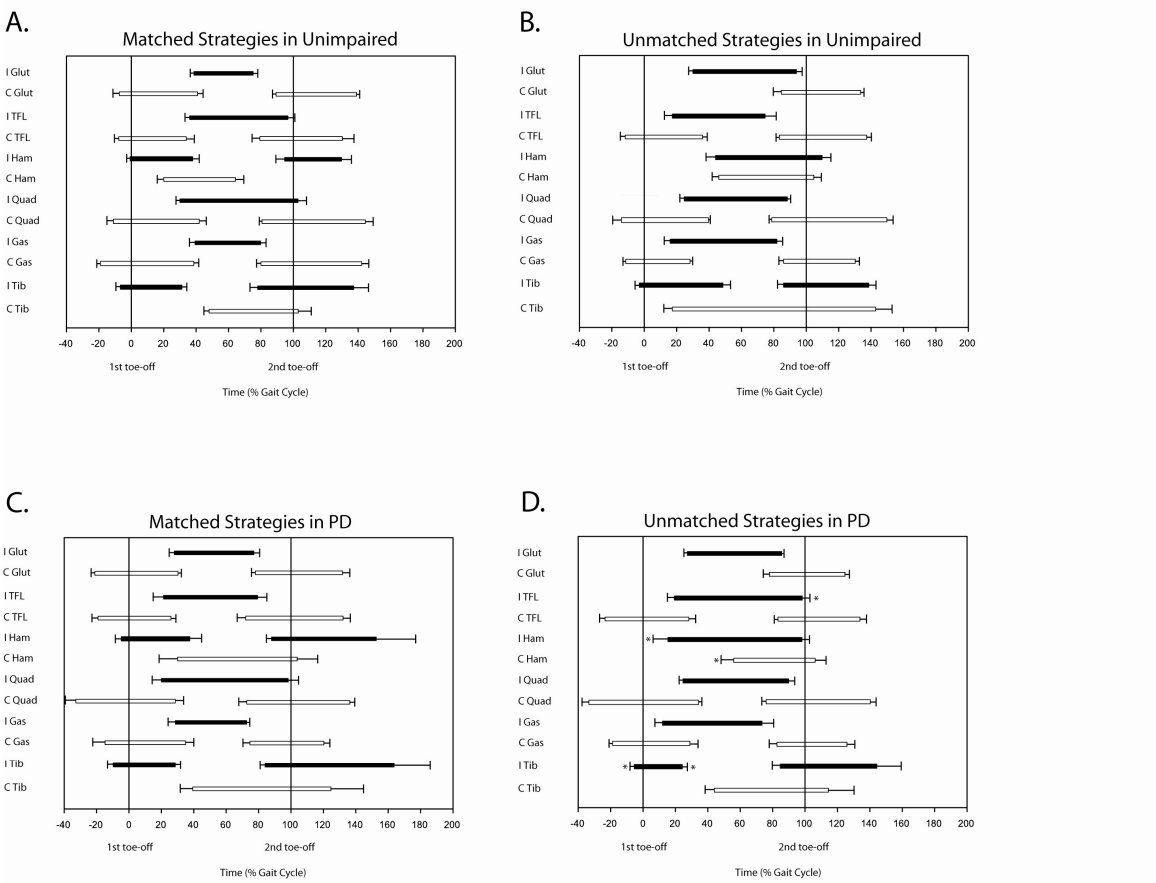
C.


R Turns Starting with R Foot - Unimpaired
R Glut
L Glut
R TFL
L TFL
R Ham
L Ham
R Quad
L Quad
R Gas
L Gas
R Tib
L Tib
-40 -20 0 20 40 60 80 100 120 140 160 180
1st toe-off
2nd toe-off
Time (% Gait Cycle)

D.


R Turns Starting with L Foot - Unimpaired
L Glut
R Glut
L TFL
R TFL
L Ham
R Ham
L Quad
R Quad
L Gas
R Gas
L Tib
R Tib
-40 -20 0 20 40 60 80 100 120 140 160 180
1st toe-off
2nd toe-off
Time (% Gait Cycle)


A.
L start L (PD)
L Glut (V)
R Glut (V)
L TFL (V)
R TFL (V)
L Ham (V)
R Ham (V)
L Quad (V)
R Quad (V)
L Gas (V)
R Gas (V)
L Tib (V)
R Tib (V)
Time (% Gati Cycle)
B.
L start R (PD)
R Glut (V)
L Glut (V)
R TFL (V)
L TFL (V)
R Ham (V)
L Ham (V)
R Quad (V)
L Quad (V)
R Gas (V)
L Gas (V)
R Tib (V)
L Tib (V)
Time (% Gait Cycle)


A.
Matched Strategies in Unimpaired
B.
Unmatched Strategies in Unimpaired
C.
Matched Strategies in PD
D.
Unmatched Strategies in PD
I Glut
C Glut
I TFL
C TFL
I Ham
C Ham
I Quad
C Quad
I Gas
C Gas
I Tib
C Tib
-40 -20 0 20 40 60 80 100 120 140 160 180 200
1st toe-off
2nd toe-off
Time (% Gait Cycle)