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Influences of elbow, shoulder, trunk motion and temporospatial parameters on arm swing asymmetry of Parkinson's disease during walking

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ABSTRACT

Arm swing asymmetry is commonly observed in early Parkinson's disease (PD) and has been found to be useful for early diagnosis. However, there are uncertainties about the nature of its relationships with gait parameters, especially shoulder and elbow motions. Therefore, this study explored how these relationships are different between PD and controls. Forty one early PD and 23 controls were included. Participants walked at self-selected speed for 3D motion analysis. Arm swing at the wrist (AS), temporospatial parameters and kinematics in elbow, shoulder and trunk were obtained. Amplitudes and asymmetries of these variables were compared between PD and control groups. PD group showed increased AS asymmetry, compared to controls. Multiple hierarchical regression analysis on AS asymmetry was conducted in order to investigate how PD influences on the relationship between AS asymmetry and other variables. In pooled data (PD and control group), asymmetries in elbow and shoulder range of motion (RoM) were significant predictors for AS asymmetry but walking speed and asymmetries in temporospatial parameters were not significant. Group effect (PD effect) was significantly mediated by only elbow RoM asymmetry. Interaction between group and elbow RoM asymmetry was statistically significant, indicating that group was an effect modifier for elbow RoM asymmetry effect on AS asymmetry. Conclusively, arm swing asymmetry measured at the wrist represents the involvement of PD effect on the unilateral and distal upper limb in early stage. These findings are helpful for future researches related to clinical applications and mechanisms of arm swing asymmetry in PD.

1. Introduction

Parkinson's disease (PD) has motor symptoms in the arms and legs, but in addition, it also has an unstable posture and/or abnormal walking patterns, especially as the disease progresses (Gelb, Oliver, & Gilman, 1999; Nieuwboer, De Weerdt, Dom, & Lesaffre, 1998). Gait related changes in PD are stooped posture, slow walking speed, shuffling, and impaired arm swing, which cause many obstacles to activities of daily living (Tan, Danoudis, McGinley, & Morris, 2012). Impaired arm swing during walking is an early and frequent motor sign in PD (Nieuwboer et al., 1998). Previously reported arm swing impairments include decreased range of motion (RoM) and increased asymmetry (Lewek, Poole, Johnson, Halawa, & Huang, 2010; Mirelman et al., 2016; Plate et al., 2015).

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Of arm swing impairments in PD, arm swing asymmetry was thought as a robust parameter independent to the change of walking speed, thereby having clinical significance (Lewek et al., 2010; Mirelman et al., 2016).

Meyns et al. postulated that arm swing is an integral part of human bipedal gait, arising mostly from passive movements, stabilized by active muscle control (Meyns, Bruijn, & Duysens, 2013). Lewek et al. postulated that arm swing could be appropriately measured at the wrist because the total amount of arm swing included elbow, shoulder and trunk motions (Lewek et al., 2010). Therefore, it is reasonable to think that arm swing measured at the wrist is influenced by walking speed, trunk motion and upper limb motions.

Locomotor arm swing is automatic motion and it operates in a stable and tightly coupled fashion with leg motions (Donker, Daffertshofer, & Beek, 2005). These imply that arm swing asymmetry may have close relationship with temporospatial asymmetry and/or kinematic asymmetry in upper limb. However, there are controversies regarding the relationships between arm swing asymmetry and temporospatial asymmetries in PD (Baltadjieva, Giladi, Gruendlinger, Peretz, & Hausdorff, 2006; Grajic, Stankovic, Radovanovic, & Kostic, 2015; Lewek et al., 2010). PD showed changes in locomotor automaticity and inter-limb coordination during early stage (Wu, Hallett, & Chan, 2015b). These changes loosen the coupling between upper and lower limb motions. Crenna et al. reported that upper limb and lower limb responded differently to treatments such as deep brain stimulation or L-dopa (Crenna et al., 2008). They postulated that human upper and lower limb locomotor automaticity is coupled according to supraspinal control modes which are heterogeneously distributed and partially independent.

There are uncertainties about the relationships between arm swing asymmetry and trunk and upper arm kinematics in PD (Becker et al., 2002; Meyns et al., 2013; Mirelman et al., 2016). Huang et al. reported that maximal cross correlation between both forearm kinematics were weaker in PD group than controls (Huang et al., 2012). Tamas et al. reported that proximal and distal arm movements should be evaluated separately, possibly due to the different somatotopic organization of subloops in the cortico-basalgangila-thalamus motor circuits (Tamas et al., 2016). Proximal muscles have bilateral innervation, while distal muscles have primarily contralateral innervation from the cortico-basalganglia-thalamus motor circuits (Montgomery, Herbert, & Buford, 2013). From these previous findings, we thought that arm swing asymmetry in PD might have complex relationships than simply reflecting passive or uniform associations. We focused on the differences between PD and controls with regard to influencing factors on arm swing asymmetry.

The objective of this study is to investigate how early PD influence on relationships between arm swing asymmetry and other variables (shoulder, elbow, trunk kinematics and temporospatial parameters). Research hypothesis are that the relationships between arm swing asymmetry and asymmetries in upper limb kinematics and temporospatial parameters are different between early PD and controls. The information gained from the current study may be helpful for the understanding and clinical application of arm swing asymmetry in PD.

2. Methods

2.1. Participants

This was a prospective observational study with convenience sampling. Participants with PD were recruited from among patients referred from the outpatient neurology department to the motion analysis laboratory in Korea University Guro Hospital for 3D gait analysis. A clinical diagnosis of PD was made according to the criteria outlined in the diagnostic criteria for PD by Gelb DJ et al. (Gelb et al., 1999). ^{18}F-FP CIT PET study was conducted to confirm PD diagnosis for all participants. Inclusion criteria for participants with PD were as follows: 1) adults with PD, 2) Hoehn and Yahr stages 1–3, 3) ambulation > 100 m without the use of an assistive device or assistance from another person, and 4) walking speed at least 0.8 m/s for community ambulation (Middleton, Fritz, & Lusardi, 2015), 5) off-drug status (drug naïve PD patients). Exclusion criteria for participants with PD included: 1) musculoskeletal problems, previous stroke or traumatic brain injury, and coexisting vestibulopathy that would restrict ambulation and 2) inability to follow two-step commands. Controls were recruited from among patients who participated in gait analysis at the motion analysis laboratory. Inclusion criteria for controls were as follows: 1) no medical history of musculoskeletal or neurological disease that would restrict ambulation, 2) no abnormal physical signs during gait inspected by an experienced physiatrist, 3) walking speed at least 0.8 m/s for community ambulation (Middleton et al., 2015), 4) no definite asymmetry in step length or swing time (differences between sides < 10% in ratio) (Balasubramanian, Neptune, & Kautz, 2010; Patterson et al., 2008). This study was approved by the institutional review board of Korea University Guro Hospital. The authors followed the policy of the institutional review board to protect the privacy and confidentiality of participants.

2.2. Measurement

The motion analysis laboratory has an 8-m level walkway, an overhead body weight support sling, and force platforms in the middle of the walkway. The ground reaction forces were measured by two force platforms (Kistler, Type 5233A, Switzerland) with 1200 Hz frequency. An optoelectronic motion analysis system (Qualisys Medical AB, Gothenburg, Sweden) was used to capture 3D trajectories of reflective markers. Eight cameras (Oqus 500+, Qualysis Sweden) were used to capture trajectories of the markers at 120 Hz. Fifty-two reflective markers were attached to each participant's trunk, arms, forearms, pelvis, thighs, legs, and feet according to the anatomical marker set recommendation by Visual3D (C-motion Inc., Rockville, Maryland, USA). The participants were allowed to walk freely in the motion analysis laboratory before the experiment to become familiar with the laboratory. After a static trial in the standing posture, the participants performed dynamic trials, walking at self-selected speeds and resting between trials to prevent fatigue. Dynamic trials were repeated until a minimum of two trials with clear kinematic and kinetic data were acquired.

2.3. Data analysis

Visual3D software was used to calculate the temporospatial, kinematic, and kinetic parameters. Joint angles were computed relative to the proximal segment. The trunk angle was the joint angle with respect to the pelvis. The shoulder angle was the joint angle with respect to the trunk. The elbow was assumed to be a hinge joint with flexion and extension, and the elbow planar angle was calculated with vectors joining the elbow center to wrist center and the elbow center to shoulder center (YuWei & HanWu, 2016). Ensemble averages were calculated within a participant, then they were used in the data analysis. Arm swing was operationally defined as wrist movement in the anterior-posterior axis (AS), which was expressed with respect to the pelvis segment (Lewek et al., 2010). Range of motion of the shoulder in the sagittal plane (RoM_shoulder), range of motion of elbow planar angle (RoM_elbow), range of motion of the trunk in the transverse plane (RoM_trunk), and the amplitude of AS were obtained during a gait cycle. Small side and large side were determined for each participants by amplitude of AS (Lewek et al., 2010). To describe the magnitude of asymmetry, the symmetry angles (SA) were calculated according to previous studies (Lewek et al., 2010; Zifchock, Davis, Higginson, & Royer, 2008). Zifchock et al. reported that SA value 0% indicates perfect symmetry, while 100% indicates that the two values are opposite(Zifchock et al., 2008). Then SA was calculated in shoulder (SA_shoulder), elbow (SA_elbow), swing time (SA_swing-time) and step length (SA_step-length) (Zifchock et al., 2008).

$$\text{Symmetry angle} = 100\% \times ((45° - \arctan(\textit{small side}/\textit{large side}))/90°)$$

2.4. Statistical analysis

Descriptive statistics, chi-square test and *t*-test were used to report the characteristics of the PD and control groups. *t*-Test was conducted to compare gait related variables between the PD and control groups. For variables without laterality such as walking speed and SAs, comparisons were conducted with the original values. For variables with laterality such as joint angles on the right and left sides, the small side in the PD was compared with the small side in the control group, and the large side was compared in the same way. To identify influences of walking speed, RoM_trunk, RoM_shoulder, and RoM_elbow on the amplitude of AS, linear regression analysis was conducted. First, simple linear regression analysis with pooled data (PD and control groups) were conducted. Second, multiple regression analysis with stepwise variable selection was conducted and relative importance of predictors were calculated with R package, “relaimpo”. Hierarchical multiple regression analysis was conducted to explore the mediators for group effect on SA_AS according to Barron & Kenny approach(R. M. Baron & Kenny, 1986). Significance of mediation was tested by Sobel test(Sobel, 1986). Hierarchical multiple regression analysis was conducted to know whether group was effect modifier (moderator) for covariate effect on SA_AS. In this analysis, mean-centering was conducted for data. Existence of significant interaction between covariate and group factor suggests that group factor is a moderator for covariate's effect on SA_AS(R. M. Baron & Kenny, 1986). Statistical significance was set at $p < .05$. R statistical software (ver. 3.3.2, Vienna, Austria) was used for the statistical analysis. The required minimum sample size was forty-nine, calculated with a 5% significance level, 80% power, effect size of 0.35, and 5 predictors for linear multiple regression by G*Power software (ver. 3.1.9.2) (Faul, Erdfelder, Buchner, & Lang, 2009; Faul, Erdfelder, Lang, & Buchner, 2007).

3. Results

3.1. Characteristics of PD and control groups

From January 1st, 2017, to May 31st, 2018, 61 participants with PD were referred for 3D gait analysis. Of the 61 participants with PD, 20 were excluded from the analysis because of drug-on status (6 participants), slow walking speed (7 participants), or other neuro-musculoskeletal problems (7 participants). The remaining 41 participants with PD were included in the analysis (PD group).

Table 1
Characteristics of the PD and control groups.

	PD (n = 41)	Control (n = 23)	p
Age (years)	63.13 (8.16)	66.37 (5.85)	0.10
Sex (female/male)	20/21	12/11	0.99
Height (m)	1.63 (0.09)	1.61 (0.07)	0.15
Weight (kg)	64.26 (14.54)	61.32 (9.43)	0.39
BMI (kg/m^2)	24.19 (3.73)	23.54 (3.00)	0.48
Duration of symptom (months)	18.14 (21.91)	N/A	
Hoehn & Yahr stage	2.05 (0.29)	N/A	
UPDRS III score	22.39 (8.45)	N/A	
MoCA score	24.29 (4.66)	N/A	

Values are mean (SD). PD, Parkinson's disease; BMI, Body mass index; UPDRS, unified Parkinson's disease rating scale; MoCA, Montreal cognitive assessment.

Table 2
Comparison of 3D motion analysis data between the PD and control group.

	Control (n = 25)	PD (n = 41)	p
Walking speed (m/s)	1.09 (0.09)	1.08 (0.16)	0.71
Cadence (steps/min)	108.78 (6.46)	111.76 (9.37)	0.14
Stride length (m)	1.19 (0.10)	1.15 (0.13)	0.15
Stride width (m)	0.10 (0.02)	0.11 (0.03)	0.48
Amplitude of AS_large (m)	0.34 (0.09)	0.30 (0.10)	0.16
Amplitude of AS_small (m)	0.28 (0.09)	0.20 (0.08)	< 0.01*
RoM_shoulder_large (°)	33.79 (12.88)	28.65 (11.53)	0.12
RoM_shoulder_small (°)	28.85 (13.11)	20.43 (9.81)	0.01*
RoM_elbow_large (°)	21.57 (9.44)	17.93 (7.73)	0.12
RoM_elbow_small (°)	20.39 (7.16)	12.82 (6.66)	< 0.01*
RoM_trunk (°)	24.45 (8.37)	18.16 (5.63)	< 0.01*
SA_AS	5.40 (4.01)	13.16 (9.54)	< 0.01*
SA_shoulder	4.91 (7.87)	10.51 (13.70)	0.04*
SA_elbow	0.92 (11.09)	10.80 (9.23)	< 0.01*
SA_swing-time	0.03 (1.84)	−0.71 (2.78)	0.20
SA_step-length	0.21 (2.15)	−0.15 (1.90)	0.51

Values are mean (SD). * denotes statistical significance $p < .05$ in t-test. 3D, three-dimensional; PD, Parkinson's disease; AS, arm swing measured at the wrist in the anterior-posterior axis; RoM, range of motion; RoM_shoulder, range of motion of the shoulder in the sagittal plane; RoM_elbow, range of motion of elbow planar angle; RoM_trunk, range of motion of the trunk in the transverse plane; SA, symmetry angle; SA_shoulder, asymmetry in the shoulder joint angle in sagittal plane; SA_elbow, asymmetry in the elbow planar angle; SA_swing-time, asymmetry in swing time; SA_step-length, asymmetry in step length.

All 41 participants in the PD group were classified in relatively early disease stages, Hoehn and Yahr stage ≤3. Their clinical characteristics are reported in Table 1. All 23 participants in the control group walked at least 0.8 m/s. Age, sex, height, weight, and body mass index did not show statistically significant differences between the PD and control groups (Table 1).

3.2. Comparison between PD and controls

Comparisons between the PD and control group are reported in Table 2. Upper limb kinematics showed significant differences in small sides but not in large sides. RoM_trunk was significantly larger in the control group. SA_AS, SA_shoulder and SA_elbow were significantly larger in the PD group.

3.3. Shoulder and elbow effects on amplitude of AS

Simple linear regression models on the amplitude of AS was conducted with pooled data (n = 64), in the small side. Walking speed ($R^2 = 0.121$, $p = .004$), RoM_shoulder in the small side ($R^2 = 0.768$, $p < .001$), RoM_elbow in the small side ($R^2 = 0.557$, $p < .001$), and RoM_trunk ($R^2 = 0.230$, $p < .001$) showed significant positive relationships with the amplitude of AS in the small side, respectively. In multiple regression analysis with variable selection, RoM_shoulder in the small side and RoM_elbow in the small side were significant predictors for amplitude of AS in the small side ($R^2 = 0.873$, $p < .001$). RoM_shoulder in the small side could explain 54.40% of multiple regression model. RoM_elbow in the small side could explain 33.29%. Group effect on amplitude of AS was mediated through RoM_shouder and RoM_elbow (Table 3).

3.4. Shoulder and elbow effects on SA_AS

In the simple linear regression models with pooled data (n = 64), SA_shoulder ($R^2 = 0.32$, $p < .01$), SA_elbow ($R^2 = 0.24$, $p < .01$), and SA_swing-time ($R^2 = 0.08$, $p = .02$) showed significant relationships with SA_AS, respectively. However, the walking speed and SA_step-length did not have a significant relationship with SA_AS. In multiple regression analysis with variable selection, SA_shoulder and SA_elbow were significant predictors for SA_AS ($R^2 = 0.45$, $p < .01$). SA_shoulder could explain 23.41% of multiple regression model and SA_elbow could explain 16.87%. In the hierarchical multiple regression analysis on SA_AS, group effect was mediated through SA_elbow but not SA_shoulder (Table 3). Group had significant interaction with SA_elbow (Table 4) (Fig. 1). This interaction accounted for a significant proportion of the variance of SA_AS ($\Delta R^2 = 0.063$, $p = .02$).

4. Discussion

This study investigated the difference of relationships between arm swing asymmetry and possible biomechanical predictors (asymmetry of shoulder, elbow, and trunk kinematics and temporospatial parameters) in PD and control groups.

Reduced arm swing amplitude is early and common sign of PD. However, recent study reported no significant difference in arm swing amplitude between early PD and controls (Baron, Koop, Streicher, Rosenfeldt, & Alberts, 2018). Lewek et al. explained this indifference by the residual effect of drugs (Lewek et al., 2010). The present study showed significant difference in the amplitude of

Table 3

Hierarchical multiple regression analysis on arm swing amplitude and asymmetry to find mediator for group effect.

Model	R^2	B for group	SE_B	β for group	*p* for β	Sobel test
DV = amplitude of AS						
1. Group (PD)	0.195	−0.084	0.022	−0.441	< 0.001	
2. Group + RoM_Shoulder	0.789	−0.029	0.011	−0.080	0.015	
Model difference (2–1)				0.361		0.004
1. Group (PD)	0.195	−0.084	0.022	−0.442	< 0.001	
2. Group + RoM_Elbow	0.567	−0.021	0.018	−0.113	0.244	
Model difference (2–1)				0.329		< 0.001
DV = SA_AS						
1. Group	0.182	7.757	2.092	0.426	< 0.001	
2. Group + SA_Shoulder	0.415	5.748	1.828	0.316	0.003	
Model difference (2–1)				−0.110		0.088
1. Group	0.182	7.757	2.092	0.426	< 0.001	
2. Group + SA_Elbow	0.297	4.751	2.174	0.261	0.033	
Model difference (2–1)				−0.165		0.004

R^2, coefficient of determination for regression model; B, regression coefficient for group effect; SE_B, standard error of regression coefficient for group effect; β, standardized regression coefficient for group effect; DV, dependent variable; AS, arm swing measured at the wrist; SA, symmetry angle; The reduction of regression coefficient for group variable between models implies that the covariance is the mediator for group effect. Sobel test is used to test statistical significance of mediator effect. * denotes statistical significance $p < .05$.

Table 4

Hierarchical multiple regression analysis on arm swing amplitude and asymmetry to find moderation effect of group factor.

	Model 1 (covariate + Group)						Model 2 (covariate x Group)					
	R^2	*p* (R^2)	B	SE_B	β	*p* (β)	R^2	*p* (R^2)	B	SE_B	β	*p* (β)
DV = amplitude of AS												
RoM_Shoulder			0.007	0.001	0.845	< 0.001*			0.006	0.001	0.773	< 0.001*
Group			−0.145	0.012	−0.080	0.227	0.764		0.012	0.010	−0.087	0.194
RoM_Shoulder x Group	0.760	< 0.001*						< 0.001*	0.001	0.001	0.095	0.302
RoM_Elbow			0.008	0.001	0.703	< 0.001*			0.007	0.002		< 0.001*
Group			−0.012	0.017	−0.071	0.453			−0.017	0.017		0.329
RoM_Elbow x Group	0.536	< 0.001*					0.549	< 0.001*	0.003	0.002		0.196
DV = SA_AS												
SA_Shoulder			0.359	0.072	0.496	< 0.001*			0.314	0.187	0.424	0.100
Group			5.748	1.828	0.316	0.003*			5.892	1.923	0.324	0.003*
SA_Shoulder x Group	0.415	< 0.001*					0.416	< 0.001*	0.053	0.203	0.066	0.794
SA_Elbow			0.304	0.096	0.377	0.002*			0.049	0.140	0.061	0.725
Group			4.751	2.174	0.261	0.033*	0.36		5.658	2.125	0.311	0.010*
SA_Elbow x Group	0.297	< 0.001*					0	< 0.001*	0.454	0.187	0.389	0.018*

R^2, coefficient of determination for regression model; B, regression coefficient for independent variables included; SE_B, standard error of regression coefficients for included variables; β, standardized regression coefficient for group effect; DV, dependent variable; AS, arm swing measured at the wrist; SA, symmetry angle; Model 1 is regression model without interaction variable. Model 2 is regression model including interaction variable. Statistically significant interaction means that group effect modified covariates' effects on dependent variables. * denotes statistical significance $p < .05$.

AS in small side between early drug-off PD and control groups, thereby supporting Lewek's postulation. In the present study, walking speeds were not significantly different between the PD and control groups, indicating that reduction of the arm swing amplitude in PD group does not stem from the walking speed change. Considering indifference in cadence and step length, these findings are consistent with previous studies in which subtle changes in PD appear first in the unilateral arm (Schneider, Drude, Kasten, Klein, & Hagenah, 2012). In this study, the trunk, shoulder and elbow motions in small side decreased in early drug-off PD. RoM_shoulder and RoM_elbow were significant predictors and mediators for group effect after multiple regression analysis. However, group effect did not have significant interaction with these covariates, thereby not modifying these effects on amplitude of AS (Table 4).

In the present study, SA_AS showed a significant difference between the PD and control groups, corresponding to previous studies (Baron, Miller Koop, Streicher, Rosenfeldt, & Alberts, 2018; Lewek et al., 2010; Plate et al., 2015). The walking speed was not a significant predictor for SA_AS. This finding is consistent with a previous study (Lewek et al., 2010). After multiple regression analysis on SA_AS, SA_shoulder and SA_elbow were selected as significant predictors. Although SA_shoulder explained large proportion of SA_AS, SA_shoulder was not a mediator for group effect. In addition, group effect did not modify SA_shoulder effect, because interaction between group and SA_shoulder was not significant (Table 4). In contrast, SA_elbow was significant mediator for group effect on SA_AS. Group effect modified SA_elbow effect with statistical significance. In the PD group, SA_AS is significantly correlated with SA_elbow but not the control group (Fig. 1). Therefore, we think that increased SA_AS (reduction of amplitude of AS in small

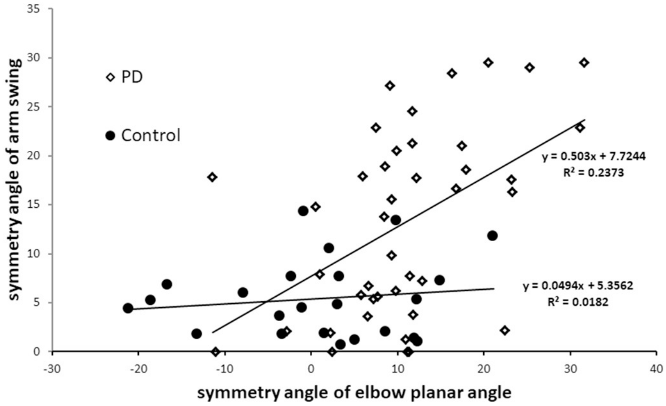

Fig. 1. The relationship between SA_elbow and SA_AS in PD and control groups. While the control group did not show a significant relationship between SA_AS and SA_elbow, the PD group had a significant positive relationship. Adding interaction term between group and SA_elbow in regression model explained significantly more proportion of model variability. AS, arm swing measured at the wrist in the anterior-posterior axis; SA, symmetry angle; SA_AS, symmetry angle of arm swing; SA_elbow, symmetry angle of elbow planar angle.

side) due to increased SA_elbow (reduction of the RoM_elbow in small side) is a PD specific finding. This is a novel finding of the present study, because there was no previous study which observed influence of shoulder and elbow asymmetries on arm swing asymmetry in early PD.

There are passive and active components in arm swing (Meyns et al., 2013). Kuhtz-Buschbeck et al. proved active components during arm swing by observing EMG activities including triceps and biceps muscles which influence elbow motions. Huang et al. measured kinematics at both forearms and reported reduction of similarity between forearm kinematics in the PD group compared to the control group (Huang et al., 2012). Based on these previous research results, we believe that our results are in line with the facts that proximal muscles have more bilateral innervation than distal muscles and that early PD have unilateral involvement of cortico-basalganglia-thalamus motor circuits (Montgomery, Herbert, & Buford, 2013). Although arm swing asymmetry improved after dopaminergic treatment or deep brain stimulation (Crenna et al., 2008; Sterling et al., 2015), there is ambiguity as to whether arm swing impairments such as coordination changes asymmetry is from dopamine depletion (Sterling et al., 2015). We think that future studies for arm swing asymmetry in PD should include not only RoM and asymmetry separately, but also proximal and distal segment kinematics and their EMG activities.

It is unclear whether temporospatial parameters are clinically significant for early diagnosis of PD (Baltadjieva et al., 2006; Djuric-Jovicic, Belic, Stankovic, Radovanovic, & Kostic, 2017; Grajic et al., 2015). Baltadjieva et al. reported significant difference of swing time asymmetry between *de novo* PD and controls (Baltadjieva et al., 2006). In contrast, Grajic et al. reported that even gait was already altered in *de novo* PD, gait symmetry remained preserved (Grajic et al., 2015). In the present study, SA_swing-time and SA_step-length did not show significant difference between PD and control groups. However, SA_swing-time showed a significant but weak relationship with SA_AS and it was not a significant predictor for SA_AS after multiple regression analysis. These findings support previous study results that there are decreased inter-limb synchronization (Winogrodzka, Wagenaar, Booij, & Wolters, 2005) and partial independence of upper and lower limb automaticity in patients with PD (Crenna et al., 2008). Consequently, asymmetry of arm swing is not only partially independent of asymmetry of lower limb but also precedes gait dysfunctions related with lower limb.

This study has some limitations. Participant's age was relatively young and concentrated in the sixties because participants visited for initial or confirmatory PD diagnosis and older subjects had less compliance with aggressive diagnosis process such as 3D gait analysis and/or 18F-FP CIT PET study. This age distribution may act as a selection bias. We included only drug off PD because to prevent medication effect on upper extremity function. We believe that exploration of motor symptoms in *de novo* PD may be helpful for the development of early diagnosis and neuroprotective intervention. Further studies with older age and/or drug on PD will be helpful for the expansion of this study results. An inclusion criterion (walking speed > 0.8 m/s) was used to exclude the effects of hidden comorbidities that may affect walking, and to maintain upper and lower limb swing ratio (1:1) due to slow walking speed below 0.8 m/s has more possibilities with different swing ratio (2:1) (Wagenaar & Emmerik, 2000). However this criterion may act as a selection bias for the relationship between arm swing asymmetry and walking speed. Therefore, interpretation of the results should be limited in PD with relatively preserved walking function, community ambulation.

While previous studies measured the amount of wrist movement in the 2D plane (Lewek et al., 2010) or in the 3D space as path length (Baron, Koop, et al., 2018), we measured the distance of wrist movement in the posterior-anterior axis with respect to the pelvis. If there are large mediolateral movements, tremors, or vertical displacements, results from these methods would differ greatly. Although it is unclear which method is most appropriate for PD, our method has limitations in reflecting mediolateral and vertical movements with respect to the pelvis. Although the participants walked at comfortable speeds in the laboratory, we could not precisely control the cognitive burden during walking, which has a significant influence on automaticity (Clark, 2015; Wu, Hallett, & Chan, 2015a).

5. Conclusion

Participants with PD showed increased arm swing asymmetry, compared to the controls. Shoulder and elbow asymmetries were significant predictors for arm swing asymmetry measured at the wrist. Although shoulder asymmetry explained larger proportion of arm swing asymmetry than elbow asymmetry, PD effect on arm swing asymmetry was mediated by only elbow asymmetry, not by shoulder asymmetry. Elbow asymmetry had significant interaction with group effect. The relationship between elbow asymmetry and arm swing asymmetry was significant in PD group whereas not in control group. Arm swing asymmetry did not have significant relationships with step length asymmetry and swing time asymmetry. Arm swing asymmetry measured at the wrist reflects the involvement of PD effect on unilateral and distal upper limb in early stage. The present findings are helpful for future researches related to clinical applications and mechanisms of arm swing asymmetry in PD.

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Declaration of Competing Interest

None.

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