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Research article

Upper-extremity kinematics and interlimb movement correlation in persons with Parkinson Disease on irregular terrain, cross-slope, and under dual-task condition

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HIGHLIGHTS

- Persons with PD had reduced arm swing magnitude compared to healthy participants.
- Persons with PD increased arm swing magnitude when their balance was challenged.
- The irregular terrain was the condition that impacted both health groups the most.
- Dual-task increased arm swing magnitude and reduced interlimb movement correlation.

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ABSTRACT

Background: A defining clinical characteristics of Parkinson disease is reduced upper-extremity movements. Irregular terrain, the presence of a cross slope, and dual-task conditions have been found to alter the lower-limb gait characteristics of persons with Parkinson disease but there is little information how different environmental and cognitive conditions impact upper-limb kinematics as well as interlimb movement correlation.
Research question: Do environmental conditions, such as irregular terrain and the presence of cross slope, as well as dual-task condition impact the upper-extremity kinematics and interlimb movement correlation of persons with Parkinson disease compared to healthy, age-matched controls?
Methods: Three-dimensional whole-body gait data were collected for nine participants with mild-to-moderate Parkinson disease and nine healthy age-matched control participants. All participants ambulated on a regular terrain, irregular terrain, with and without cross slope, and under dual and single-task conditions. The primary outcomes were arm swing magnitude, arm swing asymmetry, and normalized cross-correlation between the ipsilateral arms and contralateral legs, which characterized movement correlation.
Results: For all conditions, persons with Parkinson disease exhibited reduced arm swing magnitude and greater arm swing asymmetry compared to the healthy controls. All participants increased their arm swing magnitude on the irregular surface and under the dual-task condition. In the healthy group, the arm swing asymmetry was invariant to terrain but declined under the dual-task condition while the persons with Parkinson disease exhibited increased asymmetry on the cross slope, on the irregular terrain, and under the dual-task condition. Interlimb movement correlation decreased on the irregular terrain for the persons with Parkinson disease while the healthy group exhibited decreased interlimb movement correlation on the cross slope as well as under the dual-task condition.
Significance: Persons with Parkinson disease were able to increase their arm swing magnitude when their balance was challenged and the most significant threat to their safety as defined by the greatest reduction in the interlimb movement correlation was the irregular terrain.

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1. Introduction

The four main physical characteristics of Parkinson Disease (PD) are impairment of posture and gait, resting tremor, bradykinesia, and rigidity [1]. These characteristics have been found to significantly impact lower extremity kinematics and kinetics during walking particularly on irregular terrains [2, 3], surface transitions [4], ground-level obstacles [5], and dual-task conditions [2]. The effects of a diagnosis of PD on arm motions have also been observed in studies investigating upper-extremity kinematics [6, 7].

Affected individuals exhibit reduced arm swing during walking [6]. In fact, changes in arm swing symmetry and smoothness are observed often before other clinical markers appear [7] and has been considered as a prodromal marker for PD. Upper-extremity movements are generally considered to be mechanically passive and serve to reduce energy expenditure during able-bodied gait [8], so any changes have implications regarding gait metabolic efficiency as well as dynamic balance. Dynamic balance is important for persons with PD as it is a clinically relevant metric for establishing fall risk as determined by the Dynamic Gait Index [9]. The arm swing magnitude of persons with PD reduces as well in the presence of dual-task conditions [10]. Further, arm swing asymmetry is often significantly greater for persons with PD compared to healthy controls during level walking [11, 12]. Of note is that even with dopaminergic medication, which improves both arm swing symmetry [12] and magnitude during single-task conditions [13], these prescription regimens do not significantly impact arm swing performance during dual-task conditions [14].

Despite studies for upper and lower extremities and PD, knowledge of how the compromised motions of the upper extremities in persons with PD during level, overground walking contribute to trunk and lower-limb dynamics is limited [15, 16]. The goal of this work is to expand on this knowledge base and examine how arm motions are affected by different environmental and cognitive challenges as well as their relation to lower extremity kinematics during walking. Specifically, the magnitude of arm swing, the symmetry of movement between arms, and the interlimb movement correlation of arm swing and leg swing are quantified for three conditions that have been shown to negatively impact lower-limb and trunk dynamics. These conditions include a destabilizing irregular surface [2, 3] a cross-slope [17], and a dual-task condition [2]. Studying upper-extremity kinematics and interlimb coordination during walking on and under these conditions is important because conditions outside of level, overground walking have not been well-explored. These outcome variables quantify movements that directly contribute to the regulation of dynamic balance [18] when walking and these environmental and cognitive conditions are present in community ambulation. However, there is little evidence as to whether walking on irregular terrains, cross slopes, and under a dual-task condition would represent a threat to the dynamic stability of persons with PD or would they be able to adapt to the environment despite their known declines that are present as a function of their diagnosis. We hypothesize that persons with PD would experience a reduction in arm swing magnitude, arm swing asymmetry, and interlimb movement correlation between the arms and legs in the presence of irregular terrain, cross slope, and a dual-task condition.

2. Methods

2.1. Participants

This study recruited nine participants with PD and nine healthy, age-matched control participants (Table 1). Participants with PD were recruited as a convenience sample from the Rehabilitation and Wellness Clinic at the University of Utah's Physical Therapy Department. To be included in the study participants with PD had to be ≥50 years old, have a Hoehn & Yahr (H&Y) score between two and three, have no injury or illness that prevented participation in the study, and not have a brain stimulator implanted. The healthy, age-matched participants were enrolled if they were ≥50 years old, had no issues with balance, and no injury or illness that would prevent their involvement in the study.

Table 1. Mean (SD) participant demographic information for the participants with Parkinson disease (PD) and healthy older control (HC) group.

	Age (Years)	Height (m)	Weight (kg)	UPDRS Score	H&Y Score
PD (n = 9)	67.7 (7.1)	1.66 (0.16)	81.0 (20.6)	36.1 (11.8)	2.39 (0.33)
HC (n = 9)	67.7 (8.0)	1.69 (0.05)	74.5 (5.6)	–	–

2.2. Ethical considerations

The study protocol was approved by the University of Utah Institutional Review Board (#52667). All participants provided informed consent to participate in this study after the protocol and all associated risks were described in detail. Personally identifiable data were not collected, which maintained confidentiality of the information.

2.3. Study protocol

All participants wore tight clothing and self-selected shoes. We placed 76 reflective markers for motion tracking according to a modified Helen Hayes marker set tracking 15 segments: 2 feet, 2 shanks, 2 thighs, pelvis, trunk, head, 2 hands, 2 forearms, and 2 arms. Participants walked on each condition prior to data collection until they expressed verbal familiarity. A formal trial consisted of each participant walking back and forth wearing a safety harness that was attached to a low-friction overhead rail at a self-selected pace at least three times on each walking condition and under each cognitive condition. For trials on the cross slope, data were collected from participants walking in both directions. The first and last three steps of each trial were omitted, so the results of this study do not include gait initiation, turning, or gait termination. The order of the eight possible test conditions was randomized for each participant. Participants with PD completed all trials within 3 h of taking dopamine-replacement medication and verbally expressed they felt to be in an “ON” medication state.

2.4. Study environment

This study used a custom 7.3 m × 0.76 m walkway that could be adjusted between zero and ten degrees of cross slope. Participants ambulated on four walking conditions under two cognitive conditions. The walking conditions were regular/0-degree cross slope (exposed oriented-strand board (OSB)), irregular/0-degree cross slope (OSB covered in faux rock panels (Model R3-RV-PN-MT, Regency River Rock, FauxPanels.com)), regular/10-degree cross slope (exposed OSB with 10-degress of cross slope), and irregular/10-degree cross slope (OSB covered in faux rock panels and 10-degrees of cross slope) (Figure 1). The two cognitive conditions were dual and single task, with the dual task being serial 7 subtractions [19]. The starting number for serial-seven subtractions was randomly selected between fifty and one hundred for each dual-task trial to prevent learning effects. Twenty-four cameras (NaturalPoint, Corvallis, OR, USA) captured three-dimensional marker location data at 100 Hz, which we later filtered in Visual3D (C-motion, Germantown, MD, USA) using a dual-pass 4th order low-pass Butterworth filter at 6 Hz.

2.5. Kinematic outcomes

The three outcome variables for this study were arm swing magnitude, the non-directional arm swing asymmetry index, and the normalized cross-correlation between the arms and legs. Average walking speed was also calculated by taking the derivative of the center of mass velocity in the direction of travel. All variables were calculated between consecutive heel

Figure 1. Pictorial representation of the four possible surface conditions: Regular/0-Degree, Regular/10-Degree, Irregular/0-Degree, and Irregular/10-Degree.

strikes, which were identified using the kinematic Event TPR Signal in Visual3D [20] and verified with manual inspection. All data for each step between consecutive heel-strikes were time-normalized to 101 data points, representing 0–100% of the stride time. Arm swing magnitude (ASM), measured in meters, was calculated as the three-dimensional arc length (Eq. 1) [21] of the respective wrist centers over the course of the normalized 101 data points recorded for each step in the local coordinate frame (x,y,z) of the pelvis. In this equation, the x, y, and z variables refer to the x, y, and z coordinates of the respective wrist centers at each normalized time point t, where t ranges from $t_1 = 1$ to $t_2 = 101$.

$$ASM = \int_{t1}^{t2} \sqrt{(x'(t))^2 + (y'(t))^2 + (z'(t))^2}\, dt \tag{1}$$

The non-directional arm swing asymmetry index (ndAI) (Eq. 2) [22] expresses the interlimb difference between the time-normalized left and right wrist path length magnitudes on the scale of 0–100 over each stride, with lower values indicating better agreement between left and right. Here, L refers to the arm swing magnitude of the left arm, and R refers to the arm swing magnitude of the right arm for a single stride.

$$ndAI = ABS\left(\frac{L - R}{\max(L, R)}\right) \times 100 \tag{2}$$

The cross-correlation (CC_k) was calculated (Eq. 3) and further amplitude-normalized at a lag of $k = 0$ to get the normalized cross-correlation (nCC) using the autocorrelation of the respective signals, AcR_k and AcL_k (Eqs. (4), (5), and (6)) [23]. This measure characterizes interlimb movement correlation and compares the ipsilateral upper arm angle, θ, calculated in relationship to the torso to the contralateral thigh angle, α, calculated with respect to the vertical, both in the sagittal plane.

$$CC_k = \sum_{n=1}^{N} \theta_{R(n)} \alpha_{L(n-k)} \quad {}_{if\ n-k<0\ or\ n-k>N, then\ \alpha_{L(n-k)}=0}^{k=0,\pm1,\ldots,\pm N-1} \tag{3}$$

$$AcR_k = \sum_{n=1}^{N} \theta_{R(n)} \theta_{R(n-k)} \quad {}_{if\ n-k<0\ or\ n-k>N, then\ \theta_{R(n-k)}=0}^{k=0,\pm1,\ldots,\pm N-1} \tag{4}$$

$$AcL_k = \sum_{n=1}^{N} \alpha_{L(n)} \alpha_{L(n-k)} \quad {}_{if\ n-k<0\ or\ n-k>N, then\ \alpha_{L(n-k)}=0}^{k=0,\pm1,\ldots,\pm N-1} \tag{5}$$

$$nCC = \frac{CC_{k=0}}{\sqrt{AcR_{k=0} \times AcL_{k=0}}} \tag{6}$$

Eq. (3) represents the calculation between right arm and left leg for brevity, but it should be noted that this process was performed for the left arm and right leg as well. In the above example, AcR_k refers to the autocorrelation of the right upper arm angle with itself while AcL_k refers to the autocorrelation with the left thigh angle with itself. Normalized cross-correlation results in coefficients between -1 and 1, with values approaching either -1 or 1 indicating strong correlation. A normalized cross-correlation coefficient tending toward 1 indicate that the ipsilateral upper arm followed the motion of the contralateral thigh while a normalized cross-correlation coefficient tending toward -1 indicated the ipsilateral upper arm would swing into sagittal extension while the contralateral thigh swung into hip flexion.

2.6. Statistical analysis

The results of the three outcome variables were analyzed using Linear Mixed Effects models in MATLAB (R2020a; MathWorks, Natick, MA). Separate models were used for each outcome variable with the fixed effects being defined as health status (PD or healthy), terrain (regular or irregular), cross slope (0 or 10°), and side (left or right). Participant number represented the random effect. The data were then stratified by health and the same analysis was repeated to evaluate how the different conditions impacted the dependent variables for each health group, independently. Stratification was performed instead of investigating the interaction terms to aid in interpretability. For the data from the PD participants, the side variable was changed to "more affected" or "less affected" instead of left and right, since PD often has a more affected side. The more "more affected" side was defined as the one that had overall smaller arm swing magnitude across the regular conditions. To account for the impact walking speed has on the chosen dependent variables, walking speed was included as a continuous numeric covariate in all models. Multiple comparisons were accounted for using the Benjamini-Hochberg method [24], which suggested significance be evaluated at $p < 0.03$. All model residuals were plotted and inspected for obvious deviations from normality or homoscedasticity. We report the beta estimates in the results (Tables 3, 4, and 5). The beta estimates are utilized to determine the model-estimated mean for a specific condition. For example, for the overall model, the intercept value of 0.267m is the model-estimated mean arm swing magnitude for the healthy participants walking on the irregular surface with zero degrees of cross slope and under the dual-task condition. To determine the model-estimated mean for the participants with PD for the same conditions, the beta for Parkinson disease (beta = -0.144) is added to the intercept value. This process can be repeated for any condition or health group by adding or subtracting the associated beta values from the intercept. Consequently, the individual beta values reported in the results section show the specific magnitude and direction of change that can be expected when comparing one condition to another, such as comparing the regular terrain to the irregular terrain.

3. Results

The average walking speeds for each health group and for each condition are presented in Table 2.

Table 2. Mean (SD) walking speeds (m/s) for participants with Parkinson disease (PD) and the healthy older control particiapnts (HC) for each condition.

	PD		HC	
	Single Task	Dual Task	Single Task	Dual Task
Regular/0-Degree	0.87 (0.21)	0.74 (0.23)	1.19 (0.16)	1.09 (0.18)
Regular/10-Degree	0.87 (0.26)	0.74 (0.32)	1.18 (0.12)	1.09 (0.17)
Irregular/0-Degree	0.77 (0.28)	0.67 (0.26)	1.11 (0.18)	1.03 (0.19)
Irregular/10-Degree	0.71 (0.29)	0.65 (0.31)	1.14 (0.15)	1.04 (0.16)

3.1. Arm swing magnitude

The overall models showed that the persons with PD greatly decreased their arm swing magnitude for all conditions (beta = -0.144m, CI:-0.260,-0.027) compared to the healthy controls (Table 3). The results from all participants showed an increase in arm swing magnitude on the irregular terrain compared to the regular terrain (beta = 0.045m, CI:0.037, 0.054) (Table 3). Similarly, when walking under the dual-task condition arm swing magnitude increased for all participants (beta = 0.046m, CI: 0.036, 0.056) (Table 3). The stratified models showed that the effect size of the irregular terrain and the dual-task condition were greater for the healthy group (Table 4) than for the participants with PD (Table 5). The healthy participants had their left arm exhibit consistently greater arm swing magnitude than their right (beta = 0.079m, CI: 0.068,0.089) (Table 4).

3.2. Non-directional arm swing asymmetry index

The participants with PD had significantly greater arm swing asymmetry than the healthy control participants for all conditions (P = 0.005) (Table 3). Arm swing asymmetry increased on the irregular surface (beta = 2.90, CI:1.27,4.53), on the increased cross slope (beta = 2.49, CI:1.09,3.90), and under a dual-task condition (beta = 3.70, CI:1.96,5.44) (Table 3). The stratified models showed that the effect of terrain and cross slope observed at the population-level were primarily due to the participants with PD, and the effect size of the dual-task condition was greater for the participants with PD (beta = -5.07, CI:-7.56,-2.59) (Table 5) than it was for the healthy group (beta = -2.83, CI:-5.27,-0.40) (Table 4).

3.3. Normalized cross-correlation

The normalized cross-correlation between upper arm and thigh angle was not significantly different between health groups (P = 0.645) (Table 3). Upper arm angle was more correlated to lower leg angle on the regular surface compared to the irregular surface (beta = 0.112, CI:0.086,0.138) for all participants, and walking under the dual-task condition increased movement correlation (beta = 0.046, CI:0.015,0.074) (Table 3). In the stratified models, the participants with PD exhibited lower interlimb movement correlation on the irregular terrain (beta = -0.227, CI:-0.267,-0.187) (Table 5). The less affected upper arm showed greater movement correlation with the contralateral lower limb than the more affected upper arm (beta = 0.291, CI:0.260,0.323) (Table 5). For the healthy participants, walking on a cross slope (beta = -0.031, CI:-0.054,-0.009) and under the dual-task condition (beta = -0.081, CI:-0.110,-0.053) decreased interlimb movement correlation (Table 4), which was not observed in the model only

Table 3. Results for estimated means from the overall linear mixed effects models for the three dependent variables of interest: arm swing magnitude (ASM), non-directional arm swing asymmetry index (ndAI), and normalized cross-correlation (nCC).

		Overall			
		Beta	95% Confidence Interval		p-value
ASM(m)	Intercept	0.267	0.169	0.365	<0.001
	Parkinson Disease	**-0.144**	**-0.260**	**-0.027**	**0.016**
	Regular Surface	**-0.045**	**-0.054**	**-0.037**	**<.001**
	10° cross-slope	-0.002	-0.009	0.006	0.711
	Single Task	**-0.046**	**-0.056**	**-0.036**	**<.001**
ndAI	Intercept	9.64	-2.73	22.01	0.127
	Parkinson Disease	**15.69**	**4.83**	**26.55**	**0.005**
	Regular Surface	**-2.90**	**-4.53**	**-1.27**	**<.001**
	10° cross-slope	**2.49**	**1.09**	**3.90**	**<.001**
	Single Task	**-3.70**	**-5.44**	**-1.96**	**<.001**
nCC	Intercept	0.410	0.091	0.728	0.012
	Parkinson Disease	-0.091	-0.480	0.297	0.645
	Regular Surface	**0.112**	**0.086**	**0.138**	**<0.001**
	10° cross-slope	0.002	-0.020	0.024	0.864
	Single Task	**-0.046**	**-0.074**	**-0.015**	**0.001**

Each fixed effect has two levels. In the order of the rows, the intercepts were: Healthy Control, Irregular Surface, 0° cross-slope, and dual task. Models for each dependent variable contained walking speed as a continuous, numeric covariate. Bold indicates significance at $p < 0.03$.

Table 4. Results for estimated means from the stratified linear mixed effects models using on the data from the healthy control (HC) group for the three dependent variables of interest: arm swing magnitude (ASM), non-directional arm swing asymmetry index (ndAI), and normalized cross-correlation (nCC).

		HC Only			
		Beta	95% confidence Interval		p-value
ASM(m)	Intercept	0.288	0.152	0.425	<0.001
	Regular Surface	**-0.058**	**-0.070**	**-0.046**	**<0.001**
	10° cross-slope	-0.009	-0.020	0.002	0.106
	Single Task	**-0.065**	**-0.079**	**-0.052**	**<0.001**
	Right Side	**-0.079**	**-0.089**	**-0.068**	**<0.001**
ndAI	Intercept	12.70	-3.25	28.64	0.118
	Regular Surface	-1.20	-3.44	1.04	0.295
	10° cross-slope	1.39	-0.64	3.39	0.181
	Single Task	**-2.83**	**-5.27**	**-0.40**	**0.023**
nCC	Intercept	0.130	-0.201	0.461	0.440
	Regular Surface	-0.008	-0.034	0.017	0.524
	10° cross-slope	**-0.031**	**-0.054**	**-0.009**	**0.006**
	Single Task	**-0.081**	**-0.110**	**-0.053**	**<0.001**
	Right Side	**-0.154**	**-0.176**	**-0.132**	**<0.001**

Each fixed effect has two levels. In the order of the rows, the intercepts were: Irregular Surface, 0 Degree Cross-Slope, Dual Task, and Left Side (of the body). The ndAI models compared left side to right side so "side" was not a fixed effect. Models for each dependent variable contained walking speed as a continuous, numeric covariate. Bold indicates significance at $p < 0.03$.

Table 5. Results for estimated means from the stratified linear mixed effects models using on the data from the participants with Parkinson disease (PD) for the three dependent variables of interest: arm swing magnitude (ASM), non-directional arm swing asymmetry index (ndAI), and normalized cross-correlation (nCC).

		PD Only			
		Beta	95% Confidence Interval		p-value
ASM(m)	Intercept	0.094	0.026	0.286	0.007
	Regular Surface	**-0.033**	**-0.043**	**-0.006**	**<0.001**
	10 Degree Cross-Slope	0.004	-0.005	0.007	0.429
	Single Task	**-0.028**	**-0.039**	**0.001**	**<.001**
	Less Affected Side	**0.082**	**0.073**	**0.091**	**<.001**
ndAI	Intercept	20.45	7.58	33.33	0.002
	Regular Surface	**-4.90**	**-7.27**	**-2.53**	**<.001**
	10 Degree Cross-Slope	**3.61**	**1.63**	**5.59**	**<.001**
	Single Task	**-5.07**	**-7.56**	**-2.59**	**<.001**
nCC	Intercept	0.364	0.031	0.698	0.032
	Regular Surface	**0.227**	**0.187**	**0.267**	**<0.001**
	10 Degree Cross-Slope	0.020	-0.013	0.053	0.233
	Single Task	-0.008	-0.050	0.034	0.712
	Less Affected Side	**0.291**	**0.260**	**0.323**	**0.001**

Each fixed effect has two levels. In the order of the rows, the intercepts were: Irregular Surface, 0 Degree Cross-Slope, Dual Task, and More Affected Side(of the body). The ndAI models compared left side to right side so "side" was not a fixed effect. Models for each dependent variable contained walking speed as a continuous, numeric covariate. Bold indicates significance at $p < 0.03$.

investigating data from the participants with PD. Their left upper arm also showed greater movement correlation to the contralateral leg than their right upper arm (beta = 0.154, CI:0.132,0.176) (Table 4).

4. Discussion

For all conditions, the results demonstrated persons with PD had a reduction in arm swing magnitude and an increase in arm swing asymmetry compared to the healthy control group. This change agreed with that found by other authors for gait on a flat surface and dual-task conditions [7]. Our results further indicated that this finding extended to both irregular surfaces and cross-slope conditions. However, despite the reduction in arm swing magnitude for participants with PD relative to the controls, both groups increased their arm swing magnitude on the irregular surface as well as under the dual-task condition. These results suggest that when destabilizing surface conditions are introduced, persons with PD are still able to increase arm swing magnitude in an effort to counteract the increased whole-body dynamics generally observed in these conditions [25, 26]. This supports the concept that in some contexts, arm swing becomes an active instead of a more passive component during gait [8, 27]. It should be noted, though, that the overall effect size of this observation was relatively small.

All of the study conditions had a significant impact on arm swing asymmetry, and the effect was particularly noticeable in the participants with PD. Walking on a cross slope resulted in increased asymmetry for all participants, which we propose was performed to counteract trunk angular momentum changes seen during able-bodied gait on cross slopes that are induced by lower-limb kinematic asymmetries [28, 29]. This is, in part, supported by the findings from the normalized cross-correlation results. On the cross-slope surface, there was no significant difference between arms and legs, indicating that all participants were able to adjust their arm swing to match the contralateral limb movements. For all conditions, asymmetry increased under the dual-task condition and the interlimb movement correlation decreased. These findings were consistent with prior literature that concluded a dual-task condition magnified gait deficits both in the healthy controls as well as in persons with PD [2, 30].

The results from the health-stratified models revealed further insights into how environmental and cognitive conditions impact upper-limb movements and their correlation with the movements of the lower limbs. The irregular surface was confirmed to be a destabilizing surface [31] as observed in the increased arm swing magnitude for both groups. Though both groups increased their arm swing magnitude, the healthy group did so in a much more symmetrical and coordinated fashion than the participants with PD. These findings, coupled with those reported for lower-limb deficits on an irregular surface [2], indicate that persons with PD were especially sensitive to ground conditions and their inability to control their whole-body dynamics under postural demands [32], potentially placing them at a greater risk of falling. The healthy group consistently exhibited greater arm swing on the left side, which is a phenomenon often reported in the literature and has been attributed to the prevalence of right-handedness in the various study populations [22, 30, 33, 34].

The two health groups responded to the cross-slope condition differently. The participants with PD increased their arm swing asymmetry on the increased cross slope, but surprisingly this increase did not impact the correlation between arm and leg movements. This suggested they similarly changed their lower-limb symmetry to compensate. The healthy group conversely exhibited no change in arm swing asymmetry and the correlation between upper and lower limb movements decreased, indicating that they compensated to the cross slope primarily with alterations to their lower-limb kinematics [35].

Though the population-level analysis showed the dual-task condition to be significant for all conditions, looking at the stratified models provided a better sense as to the source of that significance. For arm swing magnitude, both groups exhibited a relatively large reduction, which agrees with previous findings that serial-7 subtractions resulted in a significant reduction in arm swing magnitude [10]. Surprisingly, the interlimb movement correlation for the participants with PD were largely unaffected by the dual-task condition. This means that regardless of the cognitive load, similar to how they adapted to the cross-slope condition, the participants with PD were able to actively adjust their lower limb movements to match the increased asymmetry in their arm swing in order to maintain as correlated arm and leg movements as possible.

This study found several important findings, but there were several limitations. Both group sizes were relatively small so increasing the sample size in future studies would increase the significance of our findings. Furthermore, though all participants had an H&Y score between 2 and 3, there were noticeable differences in arm swing characteristics between the participants with PD that were not well-captured by the reported dependent variables. An example of this would be the normalized cross-correlation metric. Some of the participants with PD showed strong negative correlation, which indicated they sometimes ambulated with almost a waddle-type gait where their ipsilateral upper and lower limbs were correlated instead of the ipsilateral upper limb and the contralateral lower limb. Future studies should focus on disease severity with greater resolution to better characterize when and how interlimb coordination will change as a function of different environmental and cognitive conditions. Finally, participants were evaluated in a medicated state. Due to the length of the protocol, it was possible that the effects of the medication changed before the end of the test trials.

5. Conclusion

Persons with PD exhibited reduced arm swing magnitude and greater arm swing asymmetry compared to the healthy control group across all surface and cognitive conditions. The irregular terrain was the greatest threat to the stability of participants with PD, as that condition had the most significant impact on arm swing magnitude, arm swing asymmetry, and interlimb movement correlation. Walking under the dual-task condition significantly impacted both health groups similarly, though that condition had no effect on the interlimb movement correlation in persons with PD. Persons with PD better adjusted to the cross-slope condition compared to the irregular condition, indicating that irregular surfaces, as well as dual-task conditions, were the largest threats to stability when walking.

In the effort to target strategies to inform clinical practice and reduce the occurrence of falls, additional research is needed to understand how persons with PD respond to irregular surface and slope conditions by managing interlimb movement correlation.

Declarations

Author contribution statement

Nicholas Gomez, MS: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

K. Bo Foreman, PhD: Conceived and designed the experiments; Analyzed and interpreted the data.

MaryEllen Hunt, MS: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

Andrew Merryweather, PhD: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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