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Investigating the Optimal Assistive Strategy for Freezing of Gait: A Comparison of Unilateral and Bilateral Artificial Muscle Assistance

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***Abstract*— As the global population continues to age, the number of individuals with Parkinson's disease (PD) is projected to increase significantly. Freezing of Gait (FoG), a common motor symptom in PD, affects more than half of patients and becomes more prevalent with disease progression. Suppression of FoG is essential for improving quality of life (QoL), and various assistive strategies have been proposed. This study evaluates the effectiveness of unilateral versus bilateral assistance using the Unplugged Suit for PD Patients (UPS-PD), a wearable gait assistive device powered by pneumatic artificial muscles. While prior UPS-PD studies examined only unilateral assist, bilateral assist has not been comparatively investigated. A slalom walking experiment was conducted as a single-case study with one PD participant under both assist conditions. The results indicated that bilateral assist produced more favorable gait patterns, including reduced gait asymmetry, increased swing duration, lower %DLS, and smaller variability, compared with unilateral assist. These improvements were supported by medium-to-large effect sizes in key parameters. Although generalization is limited due to the single-case design, these findings provide preliminary insights into assistive strategies for FoG suppression. Future studies involving larger and more diverse cohorts are required to validate these results.**

I. INTRODUCTION

Parkinson's disease (PD) is a common progressive neurological disorder characterized by motor symptoms such as gait disturbances and tremors, as well as non-motor symptoms including cognitive impairment and depression[1]. With the global elderly population steadily increasing[2], and the incidence of PD increasing with age[3], the number of PD patients is expected to continue growing. The number of individuals with PD, which was approximately 6.9 million in 2015, is projected to reach 14.2 million by 2040[4].

There are two main approaches to the treatment of PD: pharmacological therapy and surgical intervention. However, no curative treatment has been developed to date. PD presents with a variety of motor and non-motor symptoms. Among the motor symptoms, gait disturbances such as Freezing of Gait (FoG), which is characterized by short steps and asymmetric gait, are observed in PD[5]. According to Amboni et al.[6], 54% of 593 PD patients experienced FoG. Furthermore, Zhang et al.[7] reported that 50.6% of 9,072 PD patients experienced FoG, with the prevalence increasing to 64.6% among those with a disease duration of more than nine years. These findings suggest that FoG is a common symptom in PD and that alleviating FoG is essential for improving quality of life (QoL).

The "FoG threshold theory" postulates that the progressive accumulation of gait impairments may surpass a critical threshold, thereby triggering FoG episodes[8][9].

Based on the study by Okada et al.[10], we have developed a wearable pneumatic artificial muscle gait assistive device called the Unplugged Suit for PD Patients (UPS-PD)[11][12], which is activated based on the user's own leg motion to improve gait. To date, evaluations of the UPS-PD have been conducted using only unilateral assist. In this study, we developed a novel UPS-PD with bilateral assistive functionality and examined its effectiveness in a single-case study.

This design enabled a direct comparison between the conventional unilateral assist and the newly developed bilateral assist, aiming to clarify whether unilateral assist is sufficient for suppressing FoG or whether bilateral assist provides greater effectiveness. Although the number of cases is limited, this study offers preliminary evidence supporting the potential effectiveness of bilateral assist and provides fundamental insights that may serve as a basis for future large-scale clinical studies.

- Proposal of an artificial muscle assist method that more effectively alleviates gait asymmetry
- Comparison of performance between unilateral and bilateral assist

II. RELATED WORKS

A. *Strategy for FoG Suppression*

One strategy for FoG suppression involves the use of rhythmic external cues, such as auditory and visual stimuli[13]. However, previous studies have reported that the effectiveness of such cues may diminish over time[14], and that some patients exhibit weak or even adverse responses to cueing[15]. These findings suggest that the effectiveness of cue-based FoG suppression in PD patients varies significantly among individuals. According to Okada et al.[10], an experiment involving PD patients using a foot-pedaled wheelchair called "COGY," which enables movement through pedaling, demonstrated more stable and efficient locomotion compared to a conventional wheelchair, due to the regular and high-speed pedaling motion. Furthermore, Kushida et al.[16] reported that rehabilitation using COGY led to improvements in walking speed, step length, and number of steps, and that FoG observed before its use was alleviated afterward. These effects were attributed to sensory inputs—such as kinesthetic feedback, foot pressure, and visual changes—obtained

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through pedaling, which were considered to activate the thalamus. These findings suggest that, in PD patients, self-generated rhythmic movement, such as pedaling, can serve as an effective form of externally induced rhythmic stimulation, distinct from conventional cueing.

B. Assistive Device for FoG suppression

Petrucci et al.[17] developed the Portable Powered Ankle-Foot Orthosis (PPAFO), a pneumatic actuator–based device assisting ankle dorsiflexion and plantarflexion. In an experiment with 13 PD patients with FoG (Hoehn–Yahr 2.5–4), PPAFO increased the amplitude of Anticipatory Postural Adjustments (APA) and reduced toe-off time. The combination of PPAFO and auditory cueing yielded the most stable APA, suggesting that ankle assistance strengthens APA and is particularly effective for suppressing FoG when combined with auditory cues.

Kim et al.[18] conducted an experiment with a 73-year-old PD patient using a wearable device consisting of motor-driven cables and sensors designed to suppress FoG. In indoor walking trials without assistance, FoG occurred during 39% of the walking time. However, with the wearable gait assistive device, FoG episodes were completely eliminated. Additionally, the device increased walking distance by 55% and improved walking speed by 0.18 m/s. In outdoor trials as well, the wearable gait assistive device reduced FoG and increased walking distance. These results demonstrate that wearable gait assistive devices have the potential to improve walking performance and prevent FoG in patients with PD.

These findings suggest that externally applied stimulation via wearable gait assistive devices is effective for the suppression of FoG. In particular, systems that can deliver appropriate gait patterns to individuals with PD may further enhance the suppression of FoG.

C. Comparison of Unilateral and Bilateral Assist in Gait Support

Gait disturbances in neurological disorders arise from various factors, including asymmetry in cadence, a prolonged stance phase, and variability in the gait cycle. In patients with PD, such gait abnormalities are particularly associated with the onset of FoG and have been linked to an increased risk of falls. As one approach to addressing these gait impairments, wearable devices that provide external stimulation for gait support have gained attention. Consequently, there is a growing need to explore assistive strategies that can maximize the effectiveness of such interventions.

To date, no definitive conclusion has been reached regarding whether unilateral or bilateral assist is more effective in the design of gait assistive devices. For example, in the foot-pedaled wheelchair COGY developed by Okada et al.[10], bilateral pedaling is a prerequisite, suggesting that stimulation to both legs may influence gait performance. Similarly, in the study by Kim et al.[18], bilateral assist was employed, suggesting that it may produce distinct effects compared to unilateral assist. On the other hand, during steady-state walking, it is also argued that the influence of each leg may not differ significantly, and that unilateral assist may be sufficient to improve gait if the device stabilizes the gait pattern through stimulation based on the user's own leg motion. In fact, in our previous research involving the development of the UPS-PD, unilateral assist—primarily to the right leg—was used for gait support. Experiments with PD patients at Hoehn-Yahr scale stages 3 to 4 demonstrated improvements in gait, including alleviation of gait asymmetry and increased stability during the stance phase.

This study focuses on the difference between unilateral and bilateral assist and compares their effectiveness. Specifically, we developed a system based on the UPS-PD that enables bilateral assist using artificial muscles, and conducted experiments with PD patients to evaluate differences in gait improvement between unilateral and bilateral assist. Through this investigation, we aim to gain insights into optimal assistive strategies for wearable gait support devices.

III. PROPOSED SYSTEM

A. System Overview

The UPS-PD used in this study is shown in Fig. 1. It detects heel contact using a pressure sensor placed in the heel and provides timing cues for the swing phase via stimulation from pneumatic artificial muscles. The total weight of the device is approximately 1.2 kg. Compared to the unilateral-assist version of the UPS-PD, the weight has increased by about 0.2 kg; however, it remains lightweight relative to motorized gait assistive devices. The assistive force applied to one leg is approximately 30 N at most, which is substantially lower than the 80 N required by the device developed by Kim et al.[18]. Therefore, the UPS-PD is designed to support the suppression of FoG using relatively small assistive forces. The small assistive force employed in this study has the advantage of respecting the patient's walking intention without disrupting natural gait, and it may also be beneficial from the perspectives of safety and long-term rehabilitative effects. Previous studies[11][12] have suggested that externally applied stimulation, not on

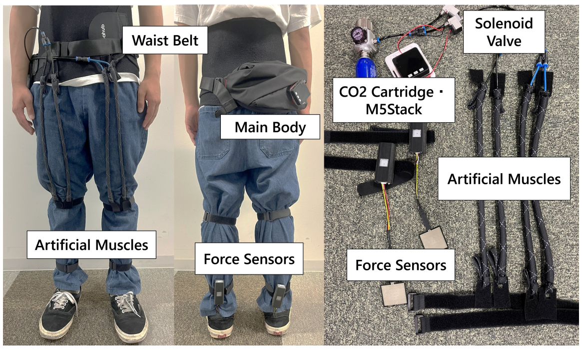


Fig. 1. UPS-PD with bilateral assist. This is designed to mount two pneumatic artificial muscles on one leg, with a corresponding force sensor attached to the heel of the opposite leg. The conventional UPS-PD configuration consisted of two artificial muscles and one force sensor. In this study, we used four artificial muscles and two force sensors.

cueing, but on the user's own leg motion, can improve gait and movement. Accordingly, it is considered that a strong assistive force capable of pulling the leg is not necessary, and that a modest yet perceivable assistive force is sufficient for the suppression of FoG. Furthermore, this system is not only lighter than other assistive devices but also easy to put on, requiring only about three minutes. The ability to don the device quickly and easily is an important aspect for reducing the burden on patients.

B. *Control Principle*

The UPS-PD provides assistance based on heel-contact detection. A pressure sensor attached to the heel detects the moment of heel strike, and the pneumatic artificial muscle on the opposite leg contracts at that time. Heel contact was defined as the instant when the vertical force measured by the heel sensor exceeded a threshold of 50 N, as expressed by the following equation:

$$\text{HeelContact}(t) = \begin{cases} 1 & \text{if } F_{\text{heel}}(t) \geq 50 \text{ N}, \\ 0 & \text{if } F_{\text{heel}}(t) < 50 \text{ N}. \end{cases}$$

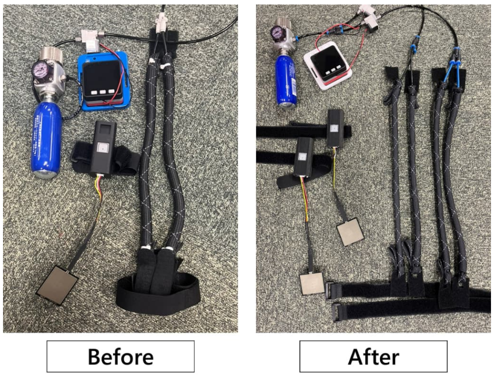
where $F_{\text{heel}}(t)$ denotes the vertical force at the heel at time t. The threshold value of 50 N was empirically determined based on preliminary observations. In this way, the system delivers assistance synchronized with the user's gait cycle, not by imposing external rhythmic cues but by reinforcing the natural rhythm generated by the user's own motion. This mechanism is intended to stabilize step timing and reduce gait asymmetry, thereby contributing to the suppression of FoG.

C. *Improvements over Previous Version*

Earlier versions of the UPS-PD were designed for unilateral assistance, typically applied to the right leg. While unilateral assist demonstrated improvements in gait, including partial alleviation of gait asymmetry, its effects were inherently limited by providing stimulation to only one side of the body. In addition, patients often reported directing disproportionate attention to the assisted leg, which could disturb natural gait rhythm.

In the present study, we extended the UPS-PD to enable bilateral assistance by equipping both legs with pneumatic artificial muscles and heel-contact pressure sensors. As shown in Fig. 2. With this improvement, the device is capable of delivering alternating assistive stimulation synchronized with the gait cycle of both legs. By distributing assistance more evenly, the new system reduces the likelihood of attentional bias toward a single leg and is expected to achieve more natural gait patterns.

This bilateral-assist version thus addresses two major limitations of the previous system: restricted asymmetry reduction and potential attentional imbalance. From the perspective of the FoG threshold theory, reducing gait asymmetry and stabilizing timing variability are critical for preventing freezing episodes. Therefore, the bilateral UPS-PD has the potential to provide more effective support for PD patients compared to the unilateral version.


Before

After

Fig. 2. UPS-PD before and after. The control system and gas cartridge remain the same, but additional foot force sensors and pneumatic artificial muscles have been implemented.

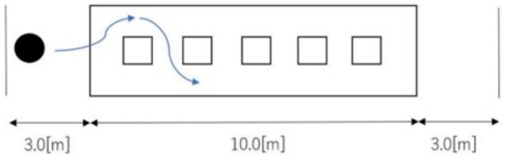


Fig. 3. The slalom walking path. In this study, the width of each chair was approximately 0.5 meters, and the experiment was conducted with seven chairs placed along the measurement path.

IV. EXPERIMENT

This study employed a single-case exploratory design, as the aim was to conduct an initial investigation into the potential differences between unilateral and bilateral assistance rather than to draw generalizable conclusions.

A. *Participant*

The participant was an 80-year-old male with PD (height: 1.65 m, weight: 57 kg), classified as Hoehn–Yahr stage 3 with a FoGQ score of 9. All measurements were conducted in the on-medication state.

B. *Experimental Setup*

The slalom walking path is shown in Fig. 3. The participant walked a total distance of 16 m, consisting of a 3 m acceleration section, a 10 m slalom walking section, and a 3 m deceleration section. Chairs were spaced at 0.8 m intervals, establishing a path width of approximately 2.5 times the participant's body width.

C. *Experimental Conditions*

Three walking conditions were tested: normal walking (Normal), right-leg assist (R-Assist), and bilateral assist (B-Assist). Each condition was performed in two trials, resulting in a total of six trials. To minimize fatigue, a 60-second rest was provided between trials. The participant wore earplugs during all trials to avoid the influence of pneumatic exhaust noise. Prior to the experiment, a short practice walk with the UPS-PD was conducted. Gait data were collected using "loadsol"[19] and the "e-skin"[20].

D. Measurements

FoG is known to occur not only at gait initiation but also in narrow spaces and during turning while walking[21]. In this study, a slalom walking path was selected as an environment to induce FoG for evaluating the effectiveness of the assistive device. On this path, step length varied considerably between straight walking and turning. Additionally, when using inertial motion capture, repeated turns can cause drift-related errors to accumulate, making it difficult to accurately measure step length. Therefore, based on the FoG threshold theory[8][9], we evaluated the following gait parameters using loadsol: unilateral cadence [steps/min] for each leg, swing phase duration [s] for each step, percentage of double limb support within a stride (%DLS), coefficient of variation of double limb support (%TotalCV), and the symmetry index (SI) during swing phase. Occurrence of FoG was determined through visual observation of video recordings obtained during the trials.

On the slalom walking path, the SI values fluctuated considerably during turning. Therefore, SI was calculated based on the swing phase duration across the entire walking trial rather than on a step-by-step basis. From the e-skin data, walking time on the slalom path and related parameters were obtained and used as reference values. %TotalCV and SI were calculated using the following equations. All data used for analysis were extracted solely from the slalom walking section, excluding the acceleration and deceleration phases.

$$\%TotalCV = \frac{SD(\%DLS)}{Mean(\%DLS)} \times 100[\%]$$

$$SI = 2 \times \left| \frac{\sum SwingTime_{left} - \sum SwingTime_{right}}{\sum SwingTime_{left} + \sum SwingTime_{right}} \right| \times 100[\%]$$

E. Data Analysis

In this study, statistical analysis was performed using the last 15 steps from each leg in each trial for the following gait parameters: unilateral cadence, swing phase duration per step, and %DLS. Accordingly, 30 steps were used for analysis on each side under each condition.

Given the single-participant design, the analysis focused on descriptive comparisons rather than inferential statistics, and no p-values were used. Instead, Cliff's delta (δ) was calculated to quantify the magnitude of differences between conditions, as it is suitable for small-sample, non-parametric comparisons.

V. RESULTS

The results for unilateral cadence under each condition are shown in Fig. 4 and Table I. The results for swing phase duration are presented in Fig. 5 and Table II, while the results for %DLS are shown in Fig. 6 and Table III. Moreover, Table IV summarizes the walking time on the slalom walking path, the %TotalCV for the left (L-%TotalCV) and right (R-%TotalCV) foot, and the SI.

In the second trial of the R-Assist condition, the participant experienced a FoG episode at gait initiation. Additionally, during the same trial, the participant passed through the chairs in an incorrect sequence, leading to a momentary loss of stability. As a result, the %TotalCV in the second R-Assist trial increased markedly. However, except for the FoG episode at gait initiation, no FoG episodes were observed during continuous walking in any of the trials.

The R-Assist condition exhibited the highest cadence for both legs with the largest within-condition variability. In contrast, the B-Assist condition resulted in the lowest unilateral cadence and the smallest standard deviations. Compared with R-Assist, cadence decreased by approximately 9.8% (left) and 2.2% (right) under B-Assist, with small effect sizes (Cliff's δ = 0.22 and -0.03, respectively).

For swing phase duration, the B-Assist condition yielded the longest durations for both legs. Compared with R-Assist, swing duration increased by approximately 3.0% in the left leg and 6.4% in the right leg, with small effect sizes (Cliff's δ = -0.04 and -0.24). These values indicate a consistent shift toward longer swing phases under bilateral assistance.

For %DLS, the B-Assist condition showed the lowest values and the smallest variability for both legs. Compared with R-Assist, %DLS decreased by 14.8% in the left leg and 12.1% in the right leg. The effect sizes were medium to large (Cliff's δ = 0.33 and 0.39), suggesting that bilateral assistance systematically reduced double-limb support relative to unilateral assistance.

SI was lowest under the B-Assist condition, indicating reduced gait asymmetry in this condition. When comparing R-Assist with B-Assist, SI decreased by approximately 37%, with a very large effect size (Cliff's δ = 1.0), although this estimate reflects only two trials per condition and should be interpreted with caution.

As shown in Table V, the effect size summary based on Cliff's δ demonstrates that medium-to-large δ values in %DLS and SI indicate a consistent shift toward more stable and symmetric gait patterns under bilateral assistance compared with unilateral assistance.

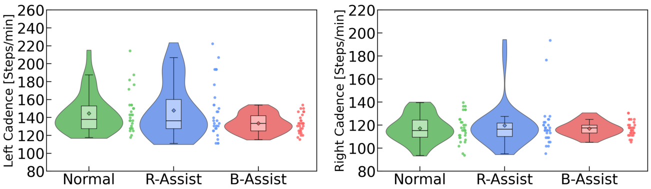


Fig. 4. Left & Right Cadence (n = 1). Normal: normal walking; R-Assist: right-leg assist; B-Assist: bilateral assist.

TABLE I. Cadence [Steps/min] (mean ± SD, n = 1)

Condition	L	R
Normal	144±22	117±12
R-Assist	148±31	119±19
B-Assist	133±10	117±6

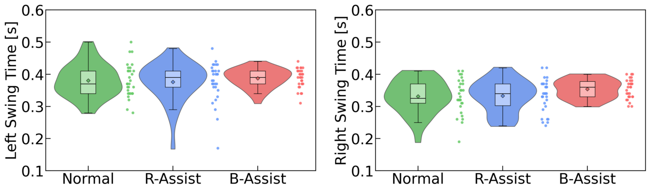


Fig. 5. Left & Right Swing Time (n = 1)

TABLE II. Swing time [s] (mean ± SD, n = 1)

Condition	L	R
Normal	0.38±0.05	0.33±0.05
R-Assist	0.38±0.06	0.33±0.05
B-Assist	0.39±0.03	0.35±0.03

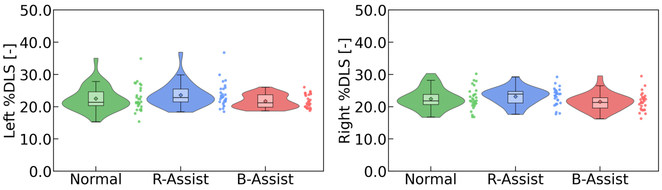


Fig. 6. Left & Right %DLS (n = 1)

TABLE III. %DLS (mean ± SD, n = 1)

Condition	L	R
Normal	22.5±3.9	22.4±3.3
R-Assist	25.5±11.0	24.5±7.9
B-Assist	21.7±2.1	21.6±2.7

TABLE IV. Gait parameters under each condition (n = 1)

Condition	Time[s]	L-%TotalCV	R-%TotalCV	SI
Normal	23.9	13.6	13.8	12.5
	26.3	17.1	19.5	15.7
R-Assist	25.5	12.7	27.3	16.9
	28.3	43.8	40.5	14.1
B-Assist	27.1	11.9	14.2	7.1
	22.0	9.2	14.1	12.3

TABLE V. Effect size summary (Cliff's δ) across all condition pairs. Positive values indicate a shift toward lower values in the second condition.

Parameter	Comparison	Left Leg	Right Leg	Interp.
Cadence	N vs R	−0.06	0.18	Small
	R vs B	0.22	−0.03	Small
	N vs B	0.18	0.15	Small
Swing Time	N vs R	0.02	−0.08	Small
	R vs B	−0.04	−0.24	Small
	N vs B	−0.02	−0.17	Small
%DLS	N vs R	0.28	0.36	Medium
	R vs B	0.33	0.39	Medium
	N vs B	0.14	0.14	Small
SI	N vs R	0.14	–	Small
	R vs B	1.00		Very Large
	N vs B	1.00		Very Large

VI. DISCUSSION

Under the B-Assist condition, swing phase duration was the longest, the stance phase proportion was reduced, and gait asymmetry was alleviated. Although statistical significance was not assessed, cadence showed a decreasing trend. These gait changes—longer swing duration, reduced stance proportion, decreased asymmetry, and smaller variability—collectively suggest that B-Assist elicited the most favorable gait pattern among the tested conditions. The consistently reduced variability further indicates a more stable and automatic gait.

During the segment corresponding to unstable gait, %DLS markedly increased, but swing phase duration did not decrease. This indicates that although the participant temporarily stopped, the leg swing motion itself remained intact. Because SI is derived from swing duration, it remained a valid indicator even during unstable gait. Consistent with this, SI showed no change under R-Assist compared with Normal, whereas B-Assist demonstrated clear improvement. While previous studies have reported that unilateral assist can alleviate gait asymmetry, the present findings suggest that bilateral assist may further enhance symmetry by promoting more balanced interlimb coordination.

When comparing B-Assist with Normal, R-%TotalCV remained stable, whereas L-%TotalCV tended to improve. In contrast, during the first R-Assist trial (in which unstable gait did not occur), R-%TotalCV worsened while L-%TotalCV improved. This pattern may reflect excessive attention directed to the assisted leg, which disrupted natural rhythm. The participant's interview comment—"I was focusing on the assist activation timing"—supports this interpretation. Under B-Assist, attentional demand was likely distributed more evenly between legs, preventing increased variability and promoting smoother movement. These observations imply that excessive conscious attention to assistive force can disturb natural gait, whereas implicit, balanced interaction—as facilitated by B-Assist—supports more stable locomotion.

From a human–robot interaction perspective, these findings underscore the importance of attentional allocation during assisted walking. Excessive cognitive focus on timing may hinder natural movement, whereas intuitive interaction promotes cooperative behavior between the user and the device. According to the FoG threshold theory, reducing cognitive load contributes to FoG alleviation; thus, the reduced attentional demand during B-Assist may have contributed to more favorable outcomes. Designing assistive strategies that minimize cognitive load and promote implicit control could therefore be essential for achieving natural gait improvement in PD.

In summary, bilateral assistance reduced gait asymmetry and variability, promoting more stable walking than unilateral assistance. While unilateral assistance provided partial benefit, bilateral strategies yielded more consistent improvements—supported by medium-to-large effect sizes—highlighting their potential advantage for stabilizing gait patterns. These preliminary findings warrant verification in larger cohorts.

VII. CONCLUSION

This study aimed to explore optimal assistive strategies in wearable gait assistive devices for suppressing Freezing of Gait (FoG) in patients with Parkinson's disease (PD). Specifically, we compared the performance of unilateral and bilateral assist using the UPS-PD to examine their relative effectiveness. Since the UPS-PD provides stimulation based on the user's own leg motion, it had been considered that unilateral assist might be sufficient for suppressing FoG. However, the results of a slalom walking task in a PD patient suggested that bilateral assist more effectively alleviated gait asymmetry and reduced variability in gait parameters, indicating potential advantages over unilateral assist.

Nevertheless, this study represents a preliminary investigation. Due to the participant's physical endurance, each condition was conducted in only two trials. Such a small number of trials increases the likelihood that unstable gait episodes disproportionately affect the overall results, potentially masking the benefits of assistance. Moreover, the participant did not present with hemiparesis, as seen in conditions such as stroke. For individuals with hemiparesis, further research is needed to determine whether bilateral assist, affected-side assist, or unaffected-side assist would be most effective.

As this is a single-case pilot study, the findings should be interpreted with caution. While the observations suggest that bilateral assist may have potential advantages over unilateral assist in alleviating gait asymmetry and reducing variability in gait parameters, these results are not generalizable. Rather, they provide preliminary evidence that bilateral assist could be more effective under certain conditions. Future studies with larger sample sizes, multiple centers, and trials conducted in real-world walking environments will be essential to confirm whether these preliminary observations hold more broadly. In addition, stratification by Hoehn–Yahr stage and investigations including individuals with hemiparesis will be needed to clarify condition- and stage-specific effects. We believe that this preliminary report offers a meaningful basis for discussion at SII and represents an important step toward larger-scale studies.

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REFERENCES

[1] Parkinson's disease | national institute of neurological disorders and stroke. [Online; accessed 2025-03-11].

[2] World population prospects 2024: Summary of results | desa publications, 7 2024. [Online; accessed 2025-03-11].

[3] K. Takahashi. Clinical management of elderly parkinson's disease patients in a super-aging society: Current status and challenges. *Japanese Journal of Neurological Therapeutics*, 39(2):51–57, 2022. (In Japanese).

[4] E. R. Dorsey and B. R. Bloem. The Parkinson Pandemic—A Call to Action. *JAMA Neurology*, 75(1):9–10, January 2018.

[5] M. Plotnik, N. Giladi, Y. Balash, C. Peretz, and J. M. Hausdorff. Is freezing of gait in Parkinson's disease related to asymmetric motor function? *Annals of Neurology*, 57(5):656–663, May 2005.

[6] M. Amboni, F. Stocchi, G. Abbruzzese, L. Morgante, M. Onofrj, S. Ruggieri, M. Tinazzi, M. Zappia, M. Attar, D. Colombo, L. Simoni, A. Ori, P. Barone, A. Antonini, and DEEP Study Group. Prevalence and associated features of self-reported freezing of gait in Parkinson disease: The DEEP FOG study. *Parkinsonism & Related Disorders*, 21(6):644–649, June 2015.

[7] W.-S. Zhang, C. Gao, Y.-Y. Tan, and S.-D. Chen. Prevalence of freezing of gait in Parkinson's disease: a systematic review and meta-analysis. *Journal of Neurology*, 268(11):4138–4150, November 2021.

[8] M. Plotnik, N. Giladi, and J. M. Hausdorff. Is freezing of gait in Parkinson's disease a result of multiple gait impairments? Implications for treatment. *Parkinson's Disease*, 2012:459321, 2012.

[9] M. Plotnik and J. M. Hausdorff. The role of gait rhythmicity and bilateral coordination of stepping in the pathophysiology of freezing of gait in Parkinson's disease. *Movement Disorders: Official Journal of the Movement Disorder Society*, 23 Suppl 2:S444–450, 2008.

[10] Y. Okada, T. Osumi, M. Okamoto, M. Narita, M. Shimizu, and S. Morioka. Examination of factors related to decreased standard wheelchair driving ability in parkinson's disease and a trial of foot-operated wheelchair use. *Movement Disorders*, 26(1):43–48, 2016. (In Japanese).

[11] A. Higuchi, J. Shiraishi, Y. Kurita, and T. Shibata. Effects of Gait Inducing Assist for Patients with Parkinson's Disease on Double Support Phase During Gait. *Journal of Robotics and Mechatronics*, 32(4):798–811, 2020.

[12] A. Higuchi, J. Shiraishi, Y. Kurita, E. Shchelkanova, Y. Ikeda, and T. Shibata. Gait Evaluation on Parkinson's Disease Patients Using Spontaneous Stimulus Induced by UPS-PD. In *2019 IEEE/SICE International Symposium on System Integration (SII)*, pages 412–416, January 2019. ISSN: 2474-2325.

[13] P. A. Rocha, G. M. Porfírio, H. B. Ferraz, and V. F. M. Trevisani. Effects of external cues on gait parameters of Parkinson's disease patients: a systematic review. *Clinical Neurology and Neurosurgery*, 124:127–134, September 2014.

[14] A. Nieuwboer, G. Kwakkel, L. Rochester, D. Jones, E. van Wegen, A. M. Willems, F. Chavret, V. Hetherington, K. Baker, and I. Lim. Cueing training in the home improves gait-related mobility in Parkinson's disease: the RESCUE trial. *Journal of Neurology, Neurosurgery, and Psychiatry*, 78(2):134–140, February 2007.

[15] S. D. Bella, D. Dotov, B. Bardy, and V. C. de Cock. Individualization of music-based rhythmic auditory cueing in Parkinson's disease. *Annals of the New York Academy of Sciences*, June 2018.

[16] H. Kushida, K. Sawada, and K. Morishita. Investigation of the potential of foot-operated wheelchair pedaling exercise in parkinson's disease rehabilitation. *Neuroscience and Rehabilitation*, 13:49–51, 2013. (In Japanese).

[17] M. N. Petrucci, C. D. MacKinnon, and E. T. Hsiao-Wecksler. Modulation of anticipatory postural adjustments using a powered ankle orthosis in people with Parkinson's disease and freezing of gait. *Gait & Posture*, 72:188–194, July 2019.

[18] J. Kim, F. Porciuncula, H. D. Yang, N. Wendel, T. Baker, A. Chin, T. D. Ellis, and C. J. Walsh. Soft robotic apparel to avert freezing of gait in Parkinson's disease. *Nature Medicine*, 30(1):177–185, January 2024.

[19] loadsol: plantar normal force inside footwear | novel.de. [Online; accessed 2025-03-10].

[20] e-skin meva | for business customers | xenoma inc. [Online; accessed 2025-03-10].

[21] M. Macht, Y. Kaussner, J. Carsten Möller, K. Stiasny-Kolster, K. M.a Eggert, H.-P. Krüger, and H. Ellgring. Predictors of freezing in Parkinson's disease: a survey of 6,620 patients. *Movement Disorders: Official Journal of the Movement Disorder Society*, 22(7):953–956, May 2007.