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Lydia Hayes Hamby April 9, 2025

Using Gait Modulation Patterns to Characterize Gait Precision Deficits in Parkinson's Disease

By

Lydia Hamby

Madeleine E. Hackney, PhD.
Adviser

Neuroscience and Behavioral Biology

Madeleine E. Hackney, PhD.

Adviser

Paul Lennard, PhD.

Committee Member

Mara Mandradjieff, PhD.

Committee Member

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Lydia Hamby

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An abstract of
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Abstract

Using Gait Modulation Patterns to Characterize and Treat Gait Precision Deficits in Parkinson's Disease

By Lydia Hamby

Importance:
Parkinson's Disease (PD) severely impacts gait adaptability, increasing fall risk when navigating everyday environments. While rehabilitation often focuses on movement accuracy, it frequently overlooks precision, or an individual's self-consistency of repeated movements, which better captures PD-related motor deficits caused by rigidity, tremors, and postural instability. Research on gait variability and adaptability in PD provides critical assessment of motor pathologies, yet studies quantifying these deficits relative to normal aging, and evaluating interventions aimed to address them, are scarce. Dance-based therapies, specifically the Spatial Gait Modulation (SGM) battery, provide a promising strategy for identifying gait precision deficits in PD.
Objective:
To characterize the effects of PD on the precision of lower-extremity joint motion during complex gait modulation patterns, relative to both younger and older adults without PD.
Study Design:
A cross-sectional study involving 36 participants, 12 younger adults (YA), 12 older adults (OA), and 12 people with PD (PWP), recruited from Emory University and the metro-Atlanta area. Participants completed standard motor-cognitive assessments and a SGM battery assessment.
Main Outcome and Measure:
Sagittal-plane joint angles of the hip, knee, and ankle were measured using OPALS sensors during all gait cycles. Precision was quantified as variability (standard deviation) of joint angles and adaptability from cycle-to-cycle (cycle-to-cycle error correction).
Results:
Participants with PD demonstrated significantly greater variability in joint angles (mean normalized SD is 0.076) compared to OA (0.057) and YA (0.053). Precision deficits were most evident during swing-phase modifications, particularly in the passe battement ($p = 0.0018$). Additionally, individuals with PD showed reduced cycle-to-cycle error correction, indicating impaired movement adaptability during swing-phase tasks ($p = 0.017$).
Conclusion and Relevance:
These findings highlight that movement precision serves as a distinct marker of PD-specific gait dysfunction beyond age-related motor changes. There is a need for dance-based therapies to explicitly address movement precision in PD.

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Introduction/Background

Introduction to Parkinson's Disease & Research on Motor Pathology

Parkinson's Disease (PD) is considered the fastest growing neurological disease in prevalence, affecting one to two people per 1000 (Dorsey et al., 2018; Zafar et al., 2023). It is estimated that PD affects around 1% of the populations exceeding the age of 60 (Zafar et al., 2023). The disease involves the progressive loss of dopaminergic neurons in the basal ganglia (Samii et al., 2004). Neurodegeneration of these nerve cells in the basal ganglia in early stages of the disease corresponds to the onset of disruptive motor-related symptoms such as tremor, muscular rigidity, postural instability, and bradykinesia (Samii et al., 2004; Fang et al., 2020). These motor impairments are often accompanied by mild to moderate cognitive deficits, particularly in executive functioning, as well as challenges in speech, visuospatial processing, and memory (Fang et al., 2020). With the advancement of motor and non-motor deficits, people with PD lose coordination and balance, which reduces their gait adaptability in the face of everyday environmental balance challenges (Pelicioni et al., 2022).

Research as explored the neural mechanisms underlying gait pathology in individuals with PD. A meta-analysis identified the involvement of multiple brain regions during gait, including the primary and premotor cortices, visual cortex, basal ganglia, and locomotor areas within the cerebellum and brainstem (Gilat et al., 2019). The basal ganglia consists of a cluster of subcortical nuclei deep in the neocortex, and it plays a critical role in motor control by determining whether movements are initiated or inhibited (Young et al., 2023). These nuclei form two interconnected motor circuits, the direct and indirect pathways, which respectively activity within these pathways is essential for smooth and adaptable gait patterns. In PD,

degeneration of dopaminergic neurons within the substantia nigra disrupts this balance, contributing to hallmark motor symptoms such as bradykinesia and rigidity (Young et al., 2023). Increased cerebellar activity driven by reliance on external gait cues has been observed as a compensatory response to impaired internally generated movement typical to an individual with PD (Peterson & Horak, 2016). Additionally, studies have reported microstructural white matter alterations within key gait-related networks. For example, individuals with PD have reduced fractional anisotropy (FA) in the corpus callosum and higher mean diffusivity (MD) in the internal and external capsules (Atkinson-Clement et al., 2017). These findings suggest compromised white matter integrity in regions critical for motor control (Atkinson-Clement et al., 2017).

Gait can further be understood by examining the two distinct phases within a gait cycle (singular stride); the swing (SW) phase, where the toes are lifted off the ground, and the stance phase (ST), where the foot contacts the ground, supporting weight (Dicharry, 2010). Within the gait cycle, it is approximated that 40% of time is spent in SW phase, and 60% in ST (Dicharry, 2010). Kinematics can be described as the 3D motion analysis lower extremity joints throughout the gait cycle (Dicharry, 2010). Kinematic studies comparing foot-floor contact sequences during straight-line walking (with a specific focus on ST phase initiation) between patients with PD and individuals without PD found that individuals with PD exhibited significantly greater atypical gait cycles (Ghislieri et al., 2021). Specifically, a higher percentage of participants with PD initiated gait with a forefoot strike rather than the typical heel strike associated with the start of the ST phase (Ghislieri et al., 2021). Existing research clearly indicates that PD impacts phases of gait, consequently impairing movement adaptability and stability. These neural and structural disruptions are likely to contribute to altered gait mechanics observed in individuals with PD.

Given these PD-related neural disruptions in gait phases, researchers typically focus on gait modulation when examining motor-related pathologies, referring to adjustment of movement patterns as required in response to context-dependent or goal-directed demands (Rosenberg et al., 2023). This impaired ability to modulate movement makes it harder to navigate everyday obstructions and pathways, putting people with PD at a greater risk of falling (Pelicioni et al., 2022). Hence, people with PD must be given therapeutics that target gait adaptability.

Motor batteries have been used to evaluate gait modulation in patients with PD, particularly when clearing obstacles (Rosenberg et al., 2023). Studies indicate that people with PD generally exhibit shorter step lengths and lower step heights when clearing obstacles in comparison to people without PD, making them more susceptible to tripping or mis-stepping (Magdalini et al., 2013; Nascimiento et al., 2021). Safe obstacle clearance relies on accuracy, ensuring the foot lands at an appropriate distance from the obstacle. A placement too short or far of a distance from the obstacle can lead to falls. Further, too small of a step height could lead to a limb getting stuck in the obstacle, also leading to a greater fall risk. Studies have also found that people with PD have greater variability in their foot placement from the obstacle and toe clearance, which corresponded with the obstacle height (lower and higher obstacle heights had greater variability than intermediate height) and the participants' severity of disease impairments (e.g. loss of balance) (Simieli et al., 2017). A lack of precision, meaning an inability to remain consistent in step height and length across multiple attempts, indicates a lack of capacity for one to consistently and predictably adapt their gait to reflect more dangerous conditions (Chou & Draganich, 1998). One can imagine how these PD-related deficits in the predictability of limb-placement trajectory extrapolate to hazardous circumstances beyond obstacle negotiation. The ability to appropriately and predictably disrupt a steady-state gait pattern is crucial to real-world

walking contexts, as humans rarely walk more than a few steps in a given direction (Orendurff et al., 2008). Gait modulation accuracy and precision, applied in context-dependent ways, are features of movement that give rise to movement adaptability and broad locomotor repertoires (Orendurff et al., 2008). Thus, research must characterize and rehabilitate the accuracy and precision of refined motor gait modulation, particularly toward PD-related deficits beyond aging alone.

The Role of Precision in PD Movement Deficits

Accuracy and precision are metrics that are often discussed in tandem, and are commonly used to evaluate motor pathologies in PD. The distinction between accuracy and precision is critical in characterizing PD-related movement deficits beyond aging. Accuracy measures how closely an outcome aligns with a target value, such as hitting the bullseye in darts, while precision refers to the consistency of outcomes across repeated trials, or how tightly grouped a player's darts are (Kumar et al., 2017). Age-related declines in range of motion can prevent individuals, whether they have PD or not, from reaching target joint angles in prescribed movements in rehabilitative therapies (Brown & Franz, 2018). For instance, research shows that hip joint flexion decreases by approximately six degrees per decade in adults between the ages of 55 and 86 (Stathokostas et al., 2013). Consequently, a person with PD may experience hip mobility deficits due to aging alone, meaning the analysis related to accuracy of their ability to reach specific joint flexion targets does not fully capture the extent of their motor pathology. PD introduces additional motor symptoms such as rigidity, tremors, and postural instability, all of which introduce additional variability in movement beyond normal aging (Fang et al., 2020). This extra variability could potentially manifest as reduced precision in movement execution. Hence, while two older adults might show similar movement accuracy levels, one with PD

would potentially exhibit more inconsistent movement patterns, alluding to a subtle yet significant deficit in motor control. By focusing on precision, assessing how consistent an individual's movements are relative to their own performance, clinicians and researchers can gain a more nuanced understanding of PD-specific motor pathology.

Within the context of PD motor pathology, measures such as variability, adaptability, error correction, and consistency are often used to describe aspects of gait control (Rosenberg et al., 2023). In this paper, the term precision is used as an overarching concept to capture and examine these descriptive motor control features, specifically referring to the internal consistency of repeated movements. Precision is closely aligned with consistency, describing how reliably a person can reproduce the same movement pattern across multiple gait cycles. Under the framework of this study, gait variability and adaptability are treated as two key attributes of precision. Variability refers to the degree of fluctuation in joint angles or movement trajectories across gait cycles, while adaptability reflects the ability to adjust movement in response to changing environmental demands, or deviance from a gait pattern (Park et al., 2016; Caetano et al., 2018). Variability and adaptability together represent the stability of an individual's motor output.

Spatiotemporal Gait Modulation in Movement Therapy

To address impairments in reliable gait modulation, Spatiotemporal Gait Modulation (SGM) patterns were developed within Dr. Hackney's lab. SGM is a set of prescribed ballet-inspired movement patterns that elicit atypical lower-extremity joint coordination during forward gait. These sequences may be implemented with or without rhythmic complexity, where irregular step timing adds a temporal dimension to movement adaptation. SGM has been previously used in biomechanics research in dance-based therapy as a tool to characterize age-related and motor-

cognitive deficits in movement accuracy. Specifically, deviations from kinematic joint targets have been used to assess individuals with mild cognitive impairment (MCI) (Rosenberg et al., 2023).

In the context of dance-based therapy, movement accuracy can be defined as the ability to replicate target joint angles, while deviations from these targets suggest an impaired ability to generate motor commands that properly modulate whole-body movement (Slusarenko et al., 2024). Prior research has shown that older adults perform SGM-based gait modifications with greater accuracy than individuals with MCI, suggesting that age-related regression in motor function, compounded by cognitive decline, limits an individual's ability to adapt spatial aspects of gait (Rosenberg et al., 2023). However, SGM has not yet been administered to individuals with PD, nor has it been coupled with a metric capturing movement precision—a critical factor in distinguishing PD-related deficits from general aging.

Study Objective and Hypothesis

As aging and PD are associated with decreased joint flexibility and reduced range of motion, I expect that older adults (OA), and to a greater extent, people with Parkinson's (PWP), will struggle to achieve prescribed movement targets, despite potentially maintaining highly precise movements (Roach & Miles, 1991; Baradan et al., 2013). The purpose of this study is to characterize the extent to which PD impairs the precision of lower-extremity joint motion beyond aging alone during complex movement sequences.

This study will define precision as the ability of individuals to replicate their own movements consistently by quantifying the variability of joint angles relative to mean joint angle performance, and the adaptability of those movements to minimize deviations across gait cycles and maintain a stable gait pattern. Given that rigidity and stiffness—hallmarks of PD motor

pathology—further restrict range of motion and movement precision, I anticipate that OA, and to a greater extent PWP, will exhibit impaired precision (Roach & Miles, 1991; Baradaran et al., 2013). My hypothesis is PWP will exhibit impaired precision (higher variability in lower-extremity joint motion) compared to OA, with deficits scaling with PD severity. OA will exhibit slight impairments in precision relative to younger adults (YA).

Materials & Methods

This protocol was approved by the IRB of Emory University under protocol IRB00003507. All participants provided informed consent and were fully apprised of the study activities. These participants are recruited through Emory University and the Atlanta area through promotions across communal groups, health fairs, and the Emory Alzheimer's Disease Research Center. All study activities occurred at a dedicated lab facility at Emory University. The inclusion protocols and study parameters are like those elaborated on in Rosenberg et al. (Rosenberg et al., 2023).

Study Design

The cross-sectional, observational setup of this study has been conducted on previously collected data from YA and OA, as well as newly collected data from people with PWP. Data collected on YA and OA was administered by Dr. Hackney, Dr. Kazanski, and Jill Bishop. Data collection for PWP was conducted by Dr. Hackney, Dr. Kazanski, Jill Bishop, Wendy Wang, and me.

All data for this study was collected in two 2-4-hour study visits for each participant. The first visit entailed a battery of standardized and validated assessments of motor and cognitive function, and the second visit entailed the administration of a series of SGM sequence protocols, which consisted of gait modulation patterns augmented with motion capture via outfitted OPAL

biomechanical sensors. All PWP participants were required to take their levodopa dose prior to the assessment to ensure they are evaluated during their ON-time period (when their dosage provides effective symptom relief).

Participants

Twelve PWP, twelve OA, and twelve YA completed the study. All YA participants are 18-35 years old. All OA and PWP are at least 50 years old. Inclusion parameters for this study include the ability to walk without assistance (e.g., walking aid) for 20 meters, at least 7 years of education, English language proficiency, no injuries or hospitalizations within the last six months, and no conditions that would affect participation or cognition (e.g. severe arthritis, uncontrolled hypertension & diabetes, renal failure, or history of angina with activity). Exclusion criteria include a stroke in the last 3 years, taking medications that could adversely affect cognition other than those treating PD (e.g., antipsychotics, opioids, stimulants, and chemotherapy), past 6 months with any substance abuse disorders, Major Depressive or Generalized Anxiety Disorders. The Table 1 provides descriptive statistics on the demographics of the participants.

Table 1: Participant Demographic Characteristics by Group

	YA (n=12)	**OA (n=12)**	**PWP (n=12)**
Age (years)	23.92 ± 4.17	67.29 ± 10.49	71.50 ± 8.56
Height (m)	1.65 ± 0.09	1.68 ± 0.10	1.73 ± 0.10
Years with PD	0	0	8.21 ± 6.02
Hoehn & Yahr Stage	N/A	N/A	1.75 ± 0.43 (n=10)
Years of Education	15.50 ± 3.20	17.50 ± 1.73	17.00 ± 2.18
Sex, n (%)			
Male	3 (25.0)	4 (33.3)	8 (66.7)

Female	9 (75.0)	8 (66.7)	4 (33.3)
Assistive Device, n (%)			
Yes	0 (0)	0 (0)	1 (8.3)
No	12 (100)	12 (100)	11 (91.7)
Dance Experience in last 5 years, n (%)			
Yes	8 (66.7)	5 (41.7)	3 (25.0)
No	4 (33.3)	7 (58.3)	9 (75.0)
Play Musical Instrument[1]	4.67 ± 2.39	4.00 ± 2.05	3.17 ± 2.08

Table 1. Values are presented as Mean ± SD for continuous variables or n (%) for categorical variables. "Hoehn & Yahr Stage" applies only to participants with PD.
[1] "Play Musical Instrument" was rated on a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree); values shown are group means ± SD.

Clinical Motor Cognitive Assessment

All participants (PWP, YA and OA) underwent a comprehensive battery of standardized and validated clinical motor and cognitive assessments to characterize aspects of motor and cognitive function.

Motor assessments were administered as follows. The 30-second Chair Stand Test (30-CST) assesses overall lower-limb strength (Jones et al., 1999). The One Leg Stance (OLS) assesses stationary balance capabilities (Jonsson, 2004). The 360-degree turn task assesses the ability to sustain balance during a quick, single turn of the entire body (Netukova et al., 2024). The simple Timed Up and Go (TUG) assesses practical movement abilities (Podsiadlo, 1991). In addition, participants executed single trials of baseline and fast walking speed for 11 meters (Rosenberg et al., 2023).

Cognitive assessments were administered, as follows. The Montreal Cognitive Assessment (MoCA) assessed overall cognitive performance (Nasreddine et al., 2005). The Trail

Making Test (TMT) assessed cognitive processing efficiency, task sequencing, and visuospatial abilities (Brown & Partington, 1942). The Reverse Corsi-Block test assessed visuospatial abilities and working memory (Corsi, 1972). The Delis-Kaplan Executive Function (D-KEFS) Tower test assessed cognitive planning elements of executive functioning (Delis et al., 1988). The Benton's Judgement of Line Orientation (B-JLo; Form) test assessed visuospatial judgment (Benton, Varney, Hamsher, 1978). Rey's Auditory Verbal Learning Test (Rey AVLT; Immediate recall) assessed short-term recall capacity, ability to acquire new information, vulnerability to distraction, and verbal recall accuracy (Rey, 1958). The Delayed Recall and Recognition form of the Rey AVLT was also conducted following a 20-30-minute delay to assess free recall and identification of verbal information (Rey, 1958). The Number Span Test, which incorporated both Forward and Backward progressions, assessed verbal short-term and working memory (Blackburn & Benton, 1957).

Participants underwent several additional assessments that evaluated integrated motor and cognitive function. The TUG-Cognitive and the TUG-manual expanded the simple TUG with simultaneous Serial-3 and water glass carrying objectives, in that order, evaluating the influence of cognitive load on movement abilities (Podsiadlo, 1991). The Body Position Spatial Task assessed combined working memory and bodily-spatial processing (Battisto et al., 2019). The Four-Square Step Test (FSST) assessed stability control during a complex stepping sequence (Dite & Temple, 2002). The participant motor and cognitive assessment descriptive statistics are provided in Table 2.

Table 2: Participant Clinical Characteristics

	YA (n=12)	**OA (n=12)**	**PD (n=12)**

Trails B-A (sec)	25.10 ± 14.62	35.70 ± 16.01	62.50 ± 28.90
Reverse Corsi Blocks (product)	52.30 ± 15.21	35.80 ± 12.40	28.40 ± 10.02
TUG Simple (sec)	6.20 ± 0.85	7.40 ± 1.20	8.90 ± 2.10
TUG Cognitive (sec)	8.50 ± 2.10	10.40 ± 3.00	12.70 ± 3.50
TUG Manual (sec)	8.20 ± 1.90	9.90 ± 2.50	11.80 ± 4.00
Chair Stands (count)	16.00 ± 3.10	13.00 ± 2.80	11.00 ± 3.50
BPST (product)	30.50 ± 10.70	22.00 ± 9.50	15.00 ± 8.20
FSST (sec)	6.80 ± 1.20	9.40 ± 2.10	10.70 ± 3.00
MoCA (points)	28.50 ± 1.10	27.50 ± 2.10	26.00 ± 3.00

Table 2. Values are Mean ± SD. TUG = Timed Up and Go; BPST = Body Position Spatial Task; MoCA = Montreal Cognitive Assessment. The score for each participant on the BPST and the Reverse Corsi Block assessments was calculated by multiplying the total number of correctly completed trials by the highest level achieved plus one. The additional level accounts for the assessment's stopping rule, which requires participants to miss two consecutive trials before stopping the assessment.

SGM Protocol

Participants executed an assessment battery as part of a protocol like that elaborated on in Rosenberg et al. (Rosenberg et al., 2023). This slightly shorter assessment battery for the study consisted of 6 spatial, 6 temporal, and 3 spatiotemporal SGM patterns. Each SGM pattern was comprised of spatial and/or temporal movement modifications. Spatial SGM involved adjusting leg joint angles during the stance or swing phases of forward movement (e.g., walking) or

throughout both phases of the gait cycle. Each spatial SGM sequence involved two distinct spatial modifications to the leg joint kinematics during gait, with one modification applied to each leg or both applied to the same leg. These spatial adjustments did not dictate step timing or rhythm. The gait modulation components used in this research (found in Figure 1; part A) were reminiscent of movements found in ballet, which altered the standard patterns of leg joint flexion and extension during walking and were tailored to be manageable for older adult individuals, including those with cognitive impairment.

This study focused on spatial SGM patterns only. Those sequence details will be elaborated on, as follows.

The 6 SGM components are categorized into three sub-classes: swing, stance, and swing-stance (Figure 1; part A). These categories were based on whether participants in the specific modulation component are instructed to adjust their joint movements during the swing phase, stance phase, or both phases of gait. Within each sub-type of gait, there were three distinct SGM patterns, which were comprised of two gait modulation components that were categorized into the specific spatial class of interest (Figure 1; part B). These patterns would be repeated upon performance within the SGM battery assessment, with the two components spanning a separate stride of the participant's gait. In swing and stance SGM patterns, each leg performed a different gait modulation component. For instance, the Coupé-Passe sequence required participants to execute the Coupé modification during the swing phase of the left leg and the Passe modification during the swing phase of the right leg. A depiction of the Coupé-Passe modification sequence is shown in Figure 2. Two modifications were applied to the same leg, while the other leg for swing-stance SGM patterns moved freely. An example is the Attitude-Relevé modification,

where the left leg performed the Attitude movement during the swing phase and the Relevé movement during the stance phase.

Figure 1: Kinematic Gait Modulation Dictionary – Library of Movement Patterns Inducing Non-Stereotypical Joint Coordination of the Lower-Extremity During Forward Gait

A **Gait modulation components**

Extracted from codified ballet fundamentals, each component induces altered within-stride swing or stance phases of gait.

	Component	Joint Targets	Cues
Swing Phase Modulated	Coupé	• 45° knee flexion • Max. ankle plantarflexion	• Swing-leg toe at stance-leg ankle
	Passé	• 90° hip flexion • Max. knee flexion	• Swing-leg toe at stance-leg knee
	Attitude	• 90° hip flexion • 90° knee flexion • Max. ankle plantarflexion	• Thigh parallel to ground • Toe points into the ground
	Développé	• 90° hip flexion • Max. early, 0° late swing knee flex. • Max. ankle plantarflexion	• Thigh parallel to ground, knee up • Extend leg out, toe points forward
	Battement	• 90° hip flexion • 0° knee flexion • Max. ankle plantarflexion	• Kick straight leg, toe points forward
Stance Phase Modulated	Piqué	• 0° knee flexion • Max. ankle plantarflexion	• Step on tip-toes, as tall as possible, with a straight leg
	Tombé	• 30° knee flexion • 30° ankle dorsiflexion	• Take large step forward, into a small-lunge
	Heel strike	• 0° knee flexion • Max. ankle dorsiflexion	• Land on heel, with a straight leg, toes pulled to shin
	Relevé	• 0° knee flexion • Max. ankle plantarflexion in mid-stance	• Land on heel, with a straight leg • Roll through foot, onto tip-toes as tall as possible

B **Gait modulation patterns**

Each pattern is the composition of two components from (A) and spans a single stride. Patterns are designated as either Swing, Stance, or Swing-Stance classes.

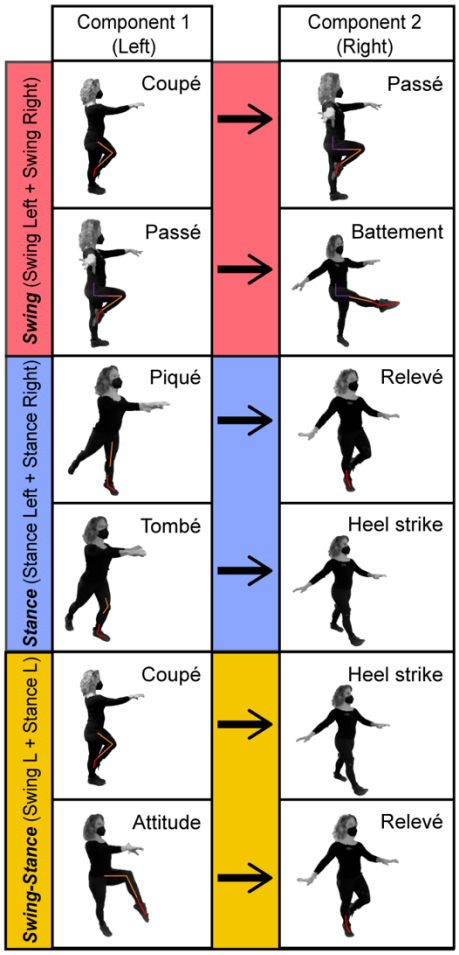
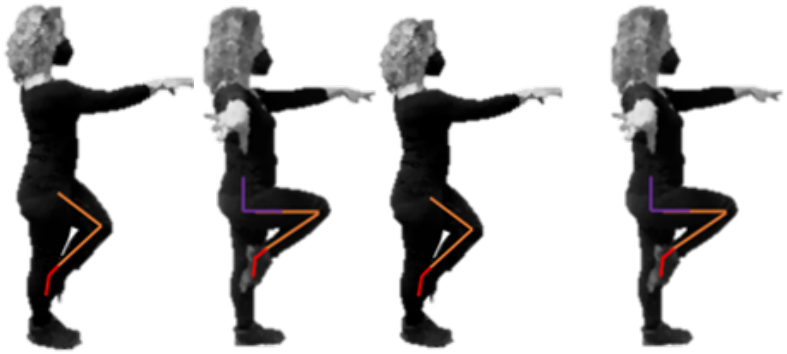


Figure 2: Innovative SGM Developed and Tested



An example from the “Spatial” Dictionary induced spatial modulations of swing phase (upper left – coupe passe). SGM patterns are sensitive and validated gait-based biomarkers (Rosenberg et al, 2023) and used in STEAM training.

SGM Assessment Protocol

Participants completed each of the 6 SGM patterns in a single session. For the YA group, SGM patterns were performed over four lengths of an 11-meter walkway. To minimize fatigue, participants in the OA and PWP groups completed each SGM pattern over a minimum of 11 meters (one walkway length) and a maximum of 4 lengths. Each participant took as much time as needed to complete each trial safely.

During the assessments, sagittal-plane joint kinematic data of the hips, knees, and ankles were collected at 128 Hz using Opal V2R inertial measurement units (APDM, Inc., Portland, USA). Fifteen sensors were placed on the forehead, sternum, lower back, and bilaterally on the

hands, wrists, upper arms, thighs, shins, and feet, following a standard setup. Joint kinematics for each trial were calculated using previously validated proprietary software (APDM Moveo Explorer).

To familiarize with each spatial SGM pattern, participants watched a tutorial video of an expert demonstrating the sequence consisting of the two prescribed gait components, then received guidance and brief practice to achieve the specific joint angle targets for the movement sequence.

SGM Assessment Data Processing

Processing biomechanical data recorded by the Opals system was performed by Dr. Kazanski using MATLAB. Individual strides in each recording were segmented using local minima and maxima in the left and right hips' range of motion, identified using MATLAB's "find peaks" method. Periods of each recording corresponding to the participant turning around during their gait were removed. Each gait cycle was then projected onto a normalized time domain (i.e., from 0% to 100% complete). Gait cycles with peaks or valleys averaging greater than two standard deviations in magnitude from an individual participant's mean were removed (indicated in red in Figure 4). After filtering out-of-distribution samples, each cycle was truncated to its central 80% of its domain by removing the first and last 10% of normalized time. Summary statistics, such as mean and standard deviation, were then computed for each of the target joints.

Gait Modulation Variability Metric

The precision of gait modulation performance was evaluated first through a variability metric of standard deviation (SD), which was used to determine a participants' ability to consistently meet their individual average lower-extremity joint angles, as opposed to the

heuristically defined targets, which may be infeasible for some populations, across the lower-extremity joints for each modification (Roach & Miles, 1991; Baradaran et al., 2013). To ensure meaningful comparisons across participants, joint angles were normalized relative to the joint's maximum range of motion in the sagittal plane. The variability metric was calculated as follows and is depicted in Equation 1. From all relevant gait phases of the kinematic time series for the sagittal-plane motion of the hip, knee, and ankle, participants' mean peak joint angles of interest were extracted from all gait cycles within the given trials. The variability from this mean performance, computed as the SD across all cycles across all joints, resulted in a single value capturing deviation from average performance, and was expressed as a percentage of the mean. Larger errors indicate a reduced ability to precisely modulate movements that prescribe spatial deviations in joint coordination patterns during gait. The SD values from all joints within a specific gait modulation pattern were averaged for each participant. From there, the mean SD was computed per population for each gait modulation pattern.

Equation 1: Variability Metric

$$\sigma = \sqrt{\frac{\Sigma\left(\theta_i - \theta_\mu\right)^2}{n-1}}$$

Equation 1. The gait modulation variability metric *s* is given in equation (1), where *s* is the standard deviation of the joint angle deviations, q_i is the i-th joint angle peak, q_m is the average joint angle peak for an individual during a specific SGM pattern, and *n* is the number of participants.

To analyze statistical differences in SD, Dr. Kazanski performed an ANOVA in R, comparing the mean SD values across the three populations for each of the six gait modulation

patterns, as presented in Table 3. The mean SD was also averaged for each of the six gait modulation patterns within their respective spatial sub-classes (stance, swing, stance-swing) and ran an ANOVA to assess differences between spatial sub-classes within each population. Finally, the overall spatial mean SD was computed for each population by averaging the mean SD values across all spatial sub-classes and performing an ANOVA to compare the differences among the three populations. Statistical significance was determined using a p-value threshold of < 0.05.

To further investigate the differences between the mean SD of the population groups identified in the mixed-effects model, a Tukey test was conducted for post hoc pairwise comparisons (as written under Table 3). In the mixed-effects model, OA were treated as the reference group, meaning that estimated effects for PWP and YA groups were calculated relative to OA. The post hoc Tukey test assessed differences between OA and PWP, and between OA and YA, but did not explicitly compare PWP and YA. Statistical significance was determined using a p value threshold of < 0.05.

Gait Modulation Adaptability Metric

To evaluate cycle-to-cycle precision, an adaptability metric was used, which assesses how precisely participants correct deviations from their average joint angle performance from one gait cycle to the next. This metric was developed by Dr. Kazanski. Unlike the first precision metric, which measures variability without consideration to sequence, this approach accounts for temporal relationships, evaluating how errors made during one cycle influence corrective adjustments in the next cycle. The adaptability metric is calculated as follows and is depicted in Equation 2. It examines the relationship between the magnitude of deviation from the participant's mean peak joint angle in one cycle (x-axis) and the correction made in the subsequent cycle (y-axis). An ideal error correction corresponds to a correction slope of negative

one, indicating perfect correction (the participant corrects precisely the magnitude of their previous deviation). A correction slope steeper (more negative) than negative one indicates overcorrection (correcting too much), while a slope flatter (less negative) than negative one indicates under correction. Plots of the cycle-to-cycle error correction across each SGM pattern for each participant were produced in MATLAB (e.g. in Figure 4, SW Passe Battement cycle-to-cycle error correction plots for ID MST009 and ID MST501).

Equation 2: Adaptability Metric

$$CC_i = \Delta\theta\Delta\theta_{i-1} \text{ where } \Delta\theta_i = \theta_i - \theta_{\mu_i}$$

Equation 2. The cycle-cycle error correction metric for the i-th stride CC_i is given in equation (2), where θ_i is the i-th joint angle peak, θ_μ is the average joint angle peak for an individual during a specific SGM pattern, and $\Delta\theta_i$ is the deviation from the i-th joint angle peak to the mean.

Correction slopes were calculated for each participant across all the SGM patterns and performed identical statistical analyses of the first precision metric with an ANOVA and post-hoc Tukey test. Statistical significance was determined using a p value threshold of < 0.05.

Statistical Analysis

Statistical analyses were conducted by Dr. Kazanski on participants' motion during the gait modulation battery assessment using OPAL biomechanical sensors. From the motion capture data, peak joint angles were extracted of the hip, knee, and ankle across all gait cycles. Descriptive statistics were computed on the gait variability metric to evaluate each population's precision performance. Standard deviation served as the overall precision metric, providing a measure of variability in joint angle performance. To assess differences in variability, an ANOVA was performed to compare the standard deviations of each population group across three factors: each gait modulation pattern, each spatial sub-class (SW, ST, or SWST), and

overall spatial class performance. Data was visualized across these factors using tables and box plots across all three groups.

Additionally, a cycle-to-cycle error control analysis was performed to examine participants' variability across successive gait cycles relative to their average joint motion. To quantify this variability, each participant's deviation from their average peak joint angle was assessed in each gait cycle. Error correction was then calculated by determining the change in peak joint angle performance in the gait cycle following the assessed cycle. To analyze this relationship, an error correction slope was derived, with deviation as the x-axis value and correction as the y-axis value. Finally, a post-hoc Tukey test was conducted to identify significant differences in error correction slopes between OA (baseline) and YA, as well as between OA and PWP. Amongst the PWP group, participants had mild to moderate diagnoses of PD which is evident based on the Hoehn & Yahr stage, with participants ranging from stages 1 to 2.5 (Hoehn & Yahr, 1967). The youngest of the YA participants was 18 years old, and the oldest was 30 years old, with an average of approximately 23 years old. The youngest of the OA participants was 53 years old, and the oldest was 80 years old, with an average of approximately 67 years old. The youngest of the PWP participants was 60 years old, and the oldest was 80 years old, with an average of approximately 72 years of age.

Results

Subjects

The subjects recruited for this study include 36 individuals, 12 YA, 12 OA, and 12 PWP. Descriptive demographic and clinical characteristic statistics of the sample are summarized in Tables 1 and 2.

Variability Results

Using MATLAB, Dr. Kazanski generated plots from the raw kinematic data, depicting the angles of a specific joint over one gait cycle. In these plots, the x-axis represents the time elapsed as a percentage (0-100%), while the y-axis represents joint angle. From these plots, the average kinematic trajectory of each lower limb joint of interest was computed for all movement modification sequences. An example of these plots for a PWP participant (ID MST501) is shown in Figure 3. Each gait modulation pattern contained a peak in joint flexion or dorsiflexion, indicating the maximum reach of movement within that sequence. The average peak value was defined as the highest average flexion or dorsiflexion angle achieved by a participant. To assess variability, the standard deviation was computed of each participant's peak joint angles relative to their own average peak joint angle performance. Figure 4 visualizes the variability in lower-limb peak joint-angle during an attitude movement, comparing performance between a PWP participant (ID MST501) and a YA participant (ID MST009). Variability is depicted as shaded purple regions representing a magnitude of one standard deviation around the mean peak joint angle, with wider shaded areas reflecting greater inconsistency in achieving desired joint angles. Individual gait cycles greater than a magnitude of two standard deviations from the mean were considered outliers (shown in red) and removed from the analysis. Notably, the PWP participant exhibited substantially larger shaded regions, indicating higher variability and reduced precision compared to the YA participant.

Figure 3: Average Lower-Limb Kinematics Across Spatial Modification Patterns

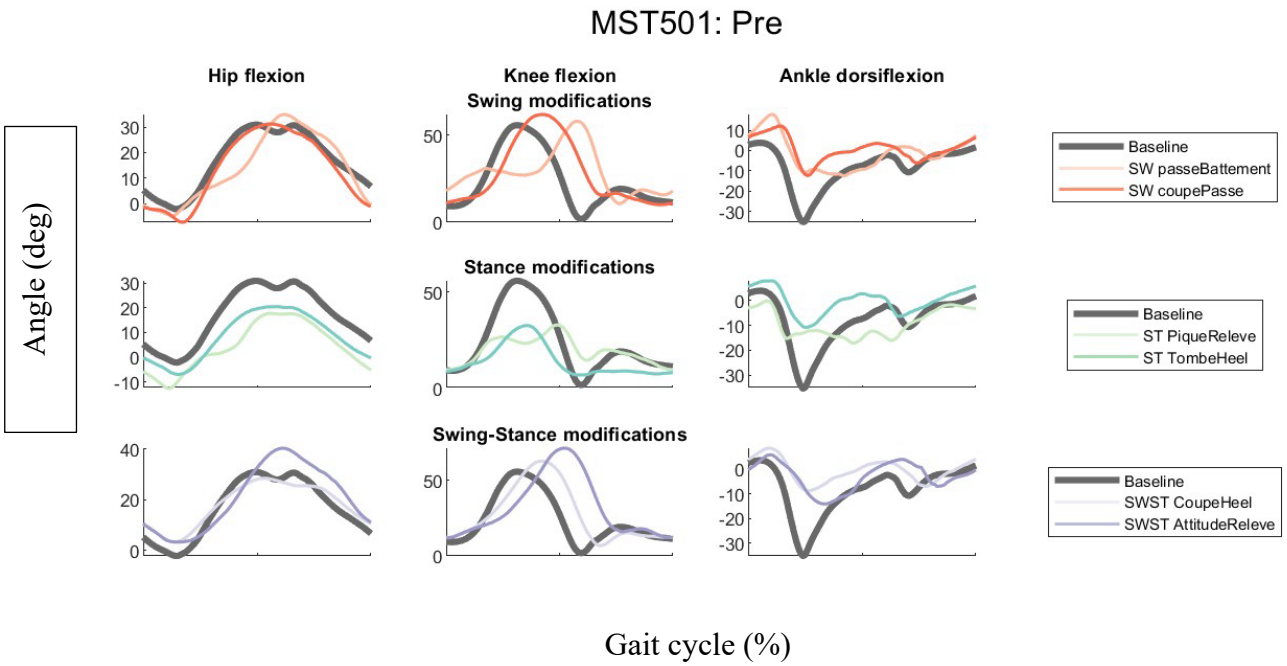


Figure 3. Mean hip, knee, and ankle joint-angle trajectories across the normalized gait cycle for baseline (typical walking pattern, depicted by dark lines) and spatial modification conditions. Each panel shows the average joint angles (in degrees plotted against the percentage of the gait cycle completion. Colored lines represent individual modification sequences grouped according to their type (Swing, Stance, and Swing-Stance). This allows for direct visual comparison of their impact on lower-limb kinematics relative to baseline.

Figure 4: Variability in Joint-Angle Kinematics During Attitude Movement in PWP and YA Participants

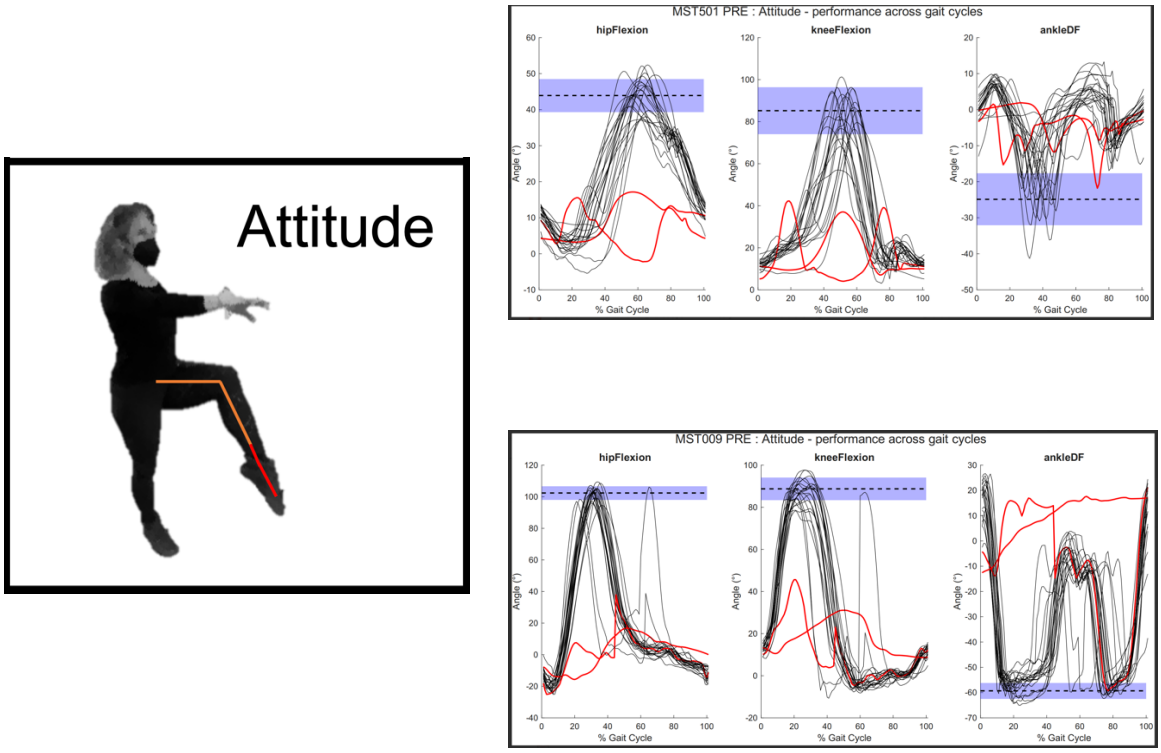


Figure 4. Variability in hip, knee, and ankle joint-angle trajectories during the attitude movement task (depicted in the image to the left), comparing a PWP participant (ID MST501), and a YA participant (ID MST009). Black lines represent individual gait cycles, and the shaded purple areas illustrate ±1 standard deviation around the mean target peak joint angles (indicated by the dashed black lines). Red lines indicate outlier gait cycles (those exceeding ±2 standard deviations from the mean) excluded from the analysis. Joint angles are normalized relative to each joint's maximum sagittal-plane range of motion which allows for standardized comparison of variability across participants.

Based on the results in the ANOVA, there was a statistically significant difference in the mean SD between the three groups in the passe battement sequence ($p < 0.001$), the SW sub-class ($p = 0.002$), and overall spatial class performance ($p = 0.003$). Based on the results in the post-hoc Tukey test, there was a statistically significant difference between PWP and OA in the passe battement sequence ($p = 0.0018$), the SW sub-class ($p = 0.0052$), and the overall spatial class performance ($p = 0.0077$). Also, the data for the normalized SD was then visualized in box

plots (as shown in Figures 5, 6, and 7) for the three different factors: each gait modulation pattern, each spatial sub-class (SW, ST, or SWST), and overall spatial class performance.

Table 3: Variability Metric Descriptive Statistics

	YA (N=11)	OA (N=12)	PD (N=11)	Total (N=34)	p value
SW Coupe Passe					**0.087**
Mean (SD)	0.054 (0.015)	0.059 (0.036)	0.083 (0.038)	0.065 (0.033)	
Range	0.035 - 0.084	0.035 - 0.163	0.047 - 0.142	0.035 - 0.163	
SW Passe Battement*					**< 0.001**
Mean (SD)	0.049 (0.019)	0.058 (0.020)	0.097 (0.039)	0.068 (0.034)	
Range	0.028 - 0.086	0.028 - 0.090	0.038 - 0.145	0.028 - 0.145	
ST Pique Releve					**0.563**
Mean (SD)	0.056 (0.016)	0.056 (0.023)	0.064 (0.022)	0.059 (0.020)	
Range	0.038 - 0.088	0.028 - 0.099	0.033 - 0.091	0.028 - 0.099	
ST Tombe Heel					**0.146**
Mean (SD)	0.041 (0.012)	0.043 (0.024)	0.058 (0.025)	0.047 (0.022)	
Range	0.024 - 0.065	0.022 - 0.103	0.027 - 0.110	0.022 - 0.110	
SWST Coupe Heel					**0.538**
Mean (SD)	0.066 (0.053)	0.050 (0.019)	0.055 (0.020)	0.057 (0.034)	

	YA (N=11)	OA (N=12)	PD (N=11)	Total (N=34)	p value
Range	0.026 - 0.219	0.031 - 0.089	0.029 - 0.092	0.026 - 0.219	
SWST Attitude Releve					**0.196**
Mean (SD)	0.052 (0.026)	0.072 (0.039)	0.078 (0.034)	0.067 (0.035)	
Range	0.026 - 0.104	0.025 - 0.136	0.045 - 0.158	0.025 - 0.158	
SW**					**0.002**
Mean (SD)	0.051 (0.014)	0.059 (0.022)	0.090 (0.035)	0.066 (0.029)	
Range	0.036 - 0.081	0.033 - 0.106	0.050 - 0.142	0.033 - 0.142	
ST					**0.169**
Mean (SD)	0.048 (0.010)	0.050 (0.016)	0.061 (0.021)	0.053 (0.017)	
Range	0.031 - 0.071	0.029 - 0.088	0.030 - 0.094	0.029 - 0.094	
SWST					**0.774**
Mean (SD)	0.059 (0.031)	0.061 (0.024)	0.067 (0.018)	0.062 (0.024)	
Range	0.028 - 0.133	0.028 - 0.107	0.044 - 0.095	0.028 - 0.133	
Spatial***					**0.003**

	YA (N=11)	OA (N=12)	PD (N=11)	Total (N=34)	p value
Mean (SD)	0.053 (0.012)	0.057 (0.012)	0.076 (0.021)	0.062 (0.018)	
Range	0.034 - 0.076	0.040 - 0.077	0.053 - 0.106	0.034 - 0.106	

Table 3. Comparison of spatial class precision through overall metric of SD among YA (N=11), OA (N=12), and PWP (N=11). Precision was measured as the variability of peak joint angles (hip, knee, and ankle) across gait cycles of each SGM pattern. Table reports mean of participants' individual SDs within each group (YA, OA, PWP), with the group's own SD (in parentheses) representing variability among participants within the group. The range shows the lowest and highest individual SD values observed, indicating the full spread of precision within each group. Measures of mean SD include the overall Spatial class, the spatial sub-classes (swing (SW), stance (ST), and swing-stance (SWST)), and the six specific SGM patterns, with the sub-class their movement components correspond to (SW Coupe Passe, SW Passe Battement, ST Pique Releve, ST Tombe Heel, SWST Coupe Heel, SWST Attitude Releve). Statistical differences among participant groups for each of these measures of mean SD were evaluated using ANOVA (statistical significance of $p < 0.05$), with significant results indicated as follows: *$p < 0.001$ (SW Passe Battement), **$p = 0.002$ (SW), and ***$p=0.003$ (Spatial). Post-hoc Tukey tests showed significant pairwise differences between PWP and OA for SW Passe Battement (*$p = 0.002$), SW (**$p = 0.005$), and spatial (***$p = 0.008$).

Figure 5: Variability Box Plot: Spatial Class

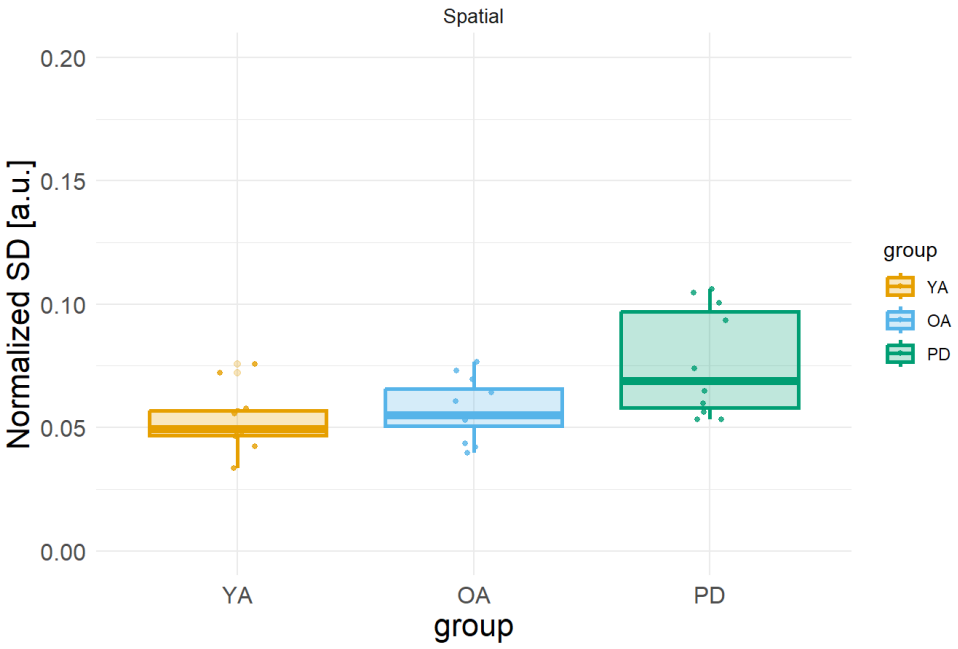


Figure 5. Box plot of normalized SD for spatial tasks across YA (yellow), OA (blue), and PWP (green). Higher values indicate greater variability in spatial class performance.

Figure 6: Variability Box Plot: Spatial Sub-Classes

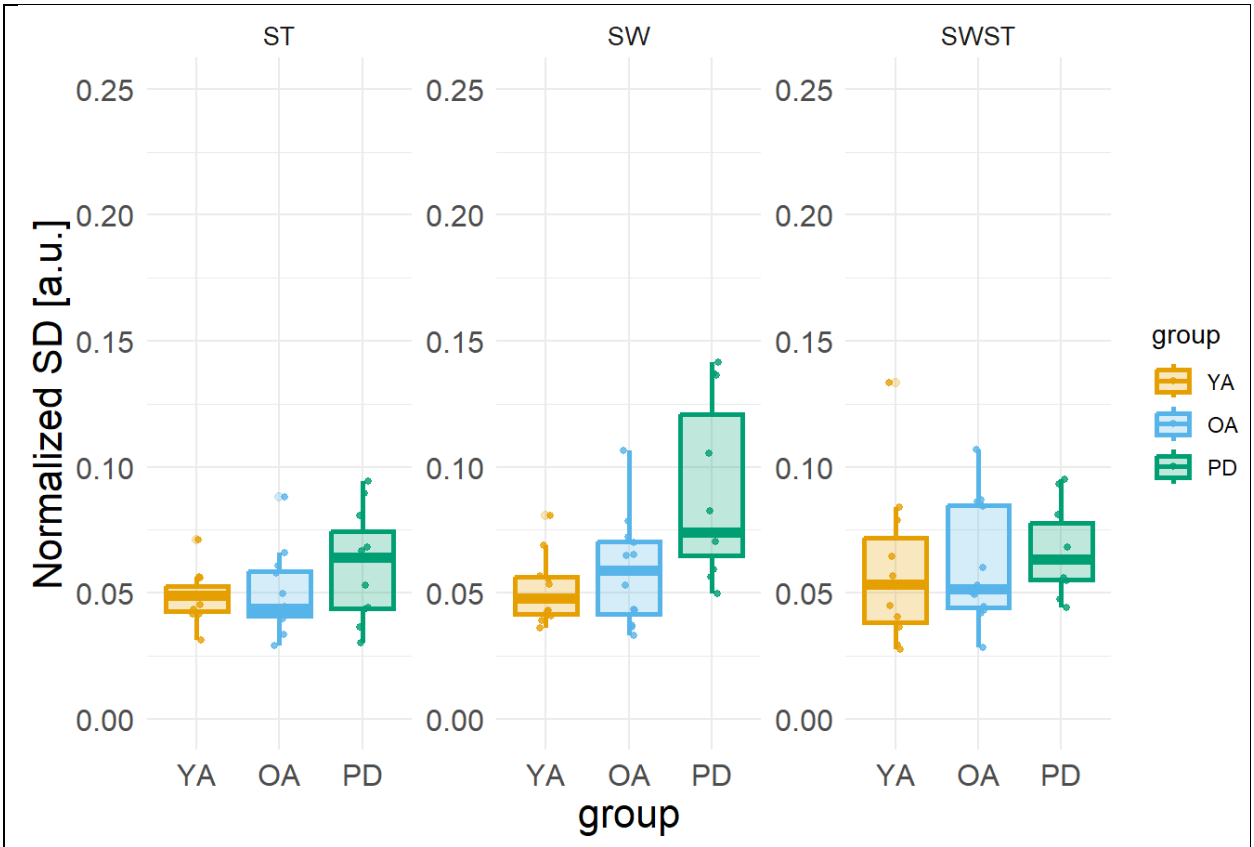


Figure 6. Box plot for normalized SD for spatial sub-classes of stance (ST), swing (SW), and swing-stance (SWST) across YA (yellow), OA (blue), and PWP (green). Higher values indicate greater variability in spatial sub-class performance.

Figure 7: Variability Box Plot: SGM Patterns

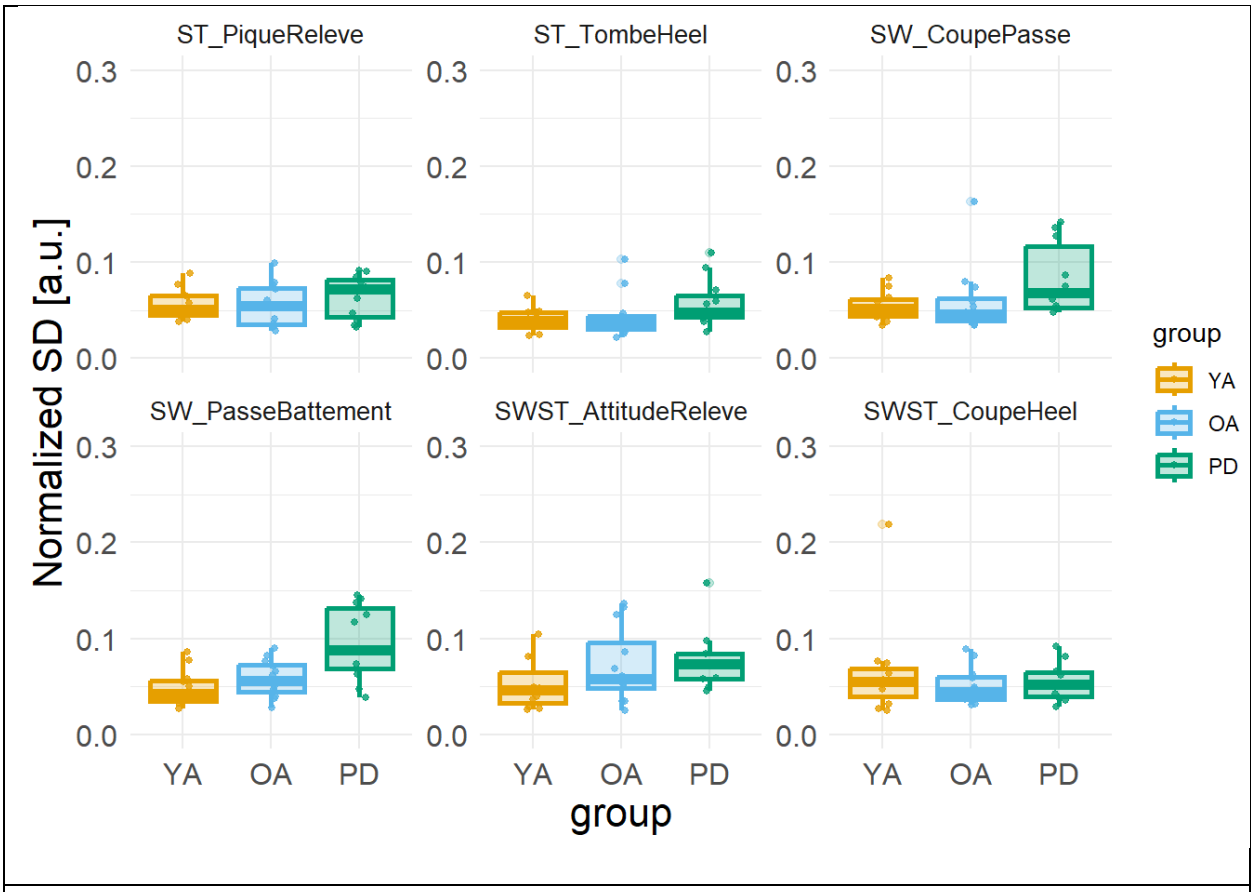


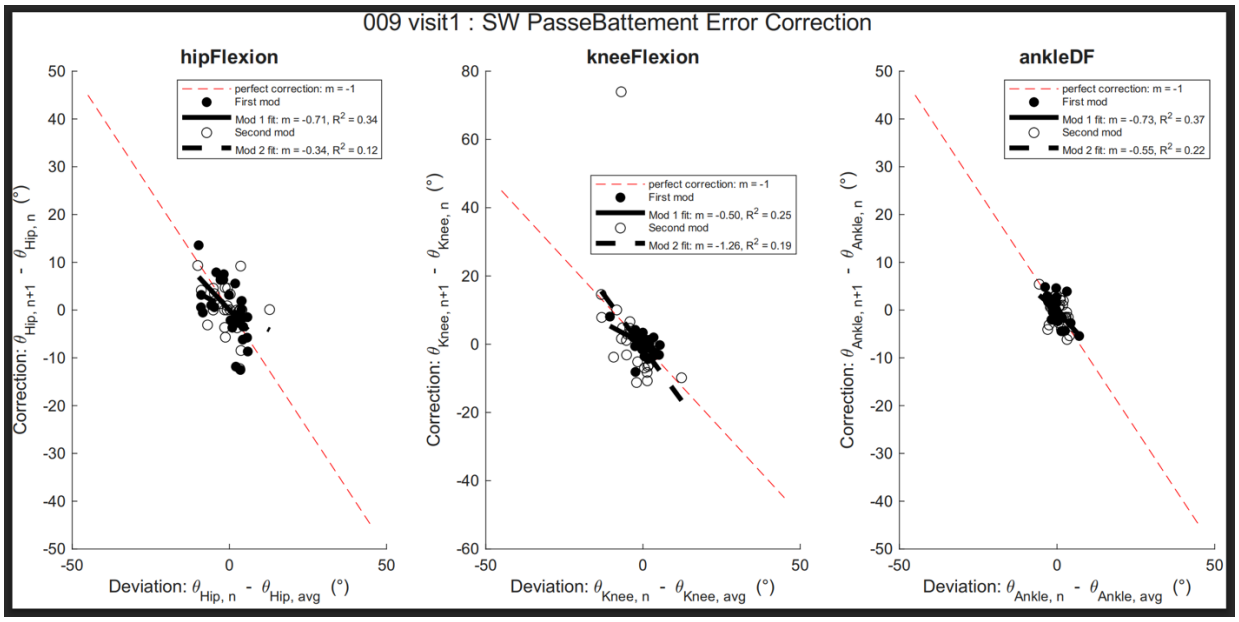
Figure 7. Box plot of normalized SD across each gait modulation pattern within the spatial sub-classes of stance (ST), swing (SW), and swing-stance (SWST) for YA (yellow), OA (blue), and PWP (green). Higher values indicate greater variability in gait modulation pattern performance.

Adaptability Results

Using MATLAB, Dr. Kazanski created cycle-to-cycle error correction plots from the raw kinematic data in each SGM pattern to examine hip flexion, knee flexion, and ankle dorsiflexion. In Figure 8, plots of the SW Passe-Battement gait pattern are shown for a PWP participant (ID MST501) and YA participant (ID MST009). The PWP participant shows correction slopes for both gait components that are further from the ideal negative one slope across all joints, demonstrating less gait adaptability and reduced precision in correcting cycle-to-cycle deviations compared to the YA participant.

Based on the results from the mean correction slope ANOVA (as depicted in Table 4), there was a statistically significant difference between the three groups in the swing-phase coupe passe sequence ($p = 0.026$) and in overall spatial performance ($p = 0.034$). Based on the result from the mean correction slope post-hoc Tukey test, there was a statistically significant difference between PWP and OA in the swing-state coupe passe sequence ($p = 0.0075$), swing-phase performance ($p = 0.017$), and overall spatial performance ($p = 0.011$). The data for the cycle-to-cycle error correction slope was then visualized in box plots (as shown in Figures 9, 10, and 11) for three different factors: each gait modulation pattern, each spatial sub-class (SW, ST, or SWST), and overall spatial class performance.

Figure 8: Cycle-to-Cycle Error Correction for SW Passe Battement in PWP and YA



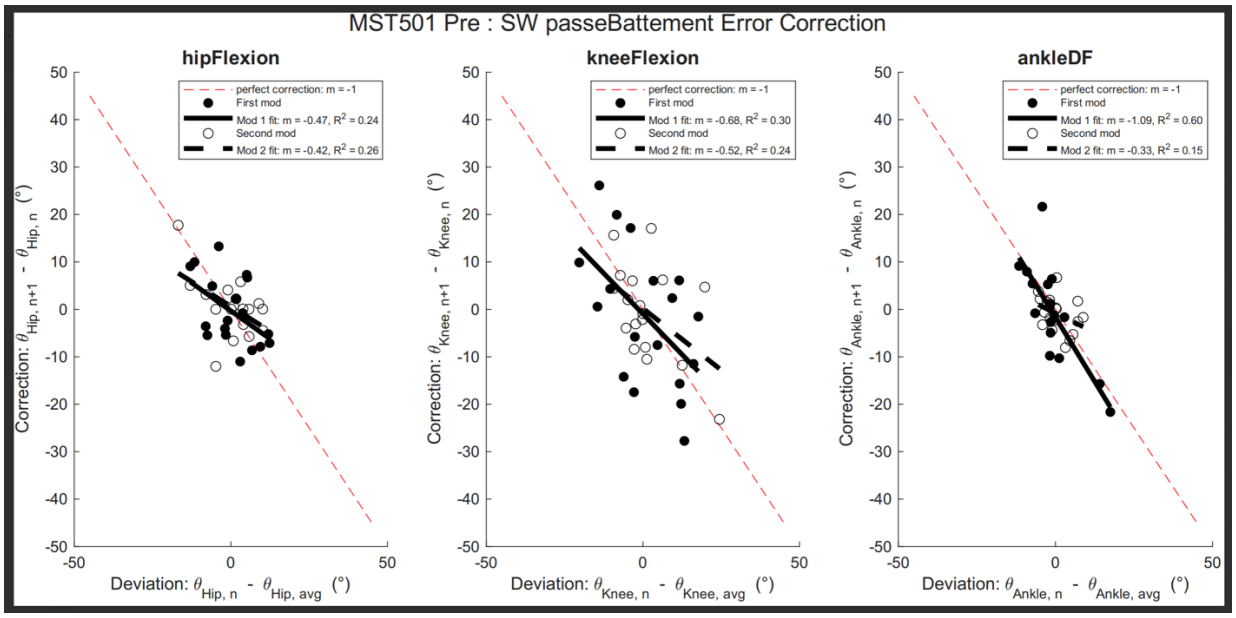


Figure 8. Cycle-to-cycle error correction plots for hip flexion, knee flexion, and ankle dorsiflexion (ankleDF) during the Swing Passe-Battement gait modification, comparing precision between a PWP participant (top; ID MST501) and a YA participant (bottom; ID MST009). Black dots represent cycle-to-cycle corrections during the first movement (Passe), while white dots represent corrections in the second movement (Battement). The solid black line indicates the average correction slope for Passe cycles, and the dashed black line indicates the average correction slope for Battement cycles. The ideal slope of perfect correction (-1, dashed red line) represents precise proportional error correction. At the top, a cycle-to-cycle error correction plot is shown for a PWP participant (ID MST501), and at the bottom is a plot of a YA participant (ID MST009).

Table 4: Adaptability Metric Descriptive Statistics

	YA (N=11)	OA (N=12)	PD (N=11)	Total (N=34)	p value
SW Coupe Passe*					0.026
Mean (SD)	-0.682 (0.269)	-0.543 (0.163)	-0.806 (0.201)	-0.669 (0.234)	
Range	-1.435 - -0.474	-0.772 - -0.229	-1.065 - -0.565	-1.435 - -0.229	
SW Passe Battement					0.473
Mean (SD)	-0.671 (0.146)	-0.663 (0.175)	-0.744 (0.186)	-0.692 (0.169)	
Range	-0.905 - -0.399	-0.904 - -0.330	-1.057 - -0.540	-1.057 - -0.330	
ST Pique Releve					0.420
Mean (SD)	-0.912 (0.239)	-0.884 (0.161)	-0.789 (0.275)	-0.862 (0.227)	
Range	-1.519 - -0.687	-1.315 - -0.658	-1.155 - -0.384	-1.519 - -0.384	
ST Tombe Heel					0.448
Mean (SD)	-0.702 (0.200)	-0.644 (0.214)	-0.763 (0.252)	-0.701 (0.221)	
Range	-1.060 - -0.465	-0.917 - -0.175	-1.147 - -0.432	-1.147 - -0.175	
SWST Coupe Heel					0.705
Mean (SD)	-0.823 (0.198)	-0.750 (0.325)	-0.827 (0.171)	-0.798 (0.241)	

	YA (N=11)	OA (N=12)	PD (N=11)	Total (N=34)	p value
Range	-1.119 - -0.514	-1.297 - -0.004	-1.078 - -0.566	-1.297 - -0.004	
SWST Attitude Releve					0.534
Mean (SD)	-0.847 (0.175)	-0.813 (0.208)	-0.906 (0.172)	-0.851 (0.185)	
Range	-1.085 - -0.576	-1.118 - -0.353	-1.201 - -0.560	-1.201 - -0.353	
SW**					0.056
Mean (SD)	-0.676 (0.141)	-0.603 (0.141)	-0.764 (0.175)	-0.679 (0.163)	
Range	-1.047 - -0.543	-0.819 - -0.361	-1.049 - -0.557	-1.049 - -0.361	
ST					0.841
Mean (SD)	-0.807 (0.186)	-0.764 (0.102)	-0.776 (0.236)	-0.782 (0.176)	
Range	-1.214 - -0.578	-0.923 - -0.614	-1.151 - -0.477	-1.214 - -0.477	
SWST					0.385
Mean (SD)	-0.835 (0.138)	-0.782 (0.197)	-0.876 (0.118)	-0.828 (0.157)	
Range	-1.036 - -0.640	-1.005 - -0.384	-1.078 - -0.737	-1.078 - -0.384	
Spatial***					0.034

	YA (N=11)	OA (N=12)	PD (N=11)	Total (N=34)	p value
Mean (SD)	-0.768 (0.052)	-0.716 (0.087)	-0.801 (0.080)	-0.760 (0.081)	
Range	-0.847 - -0.682	-0.803 - -0.528	-0.910 - -0.644	-0.910 - -0.528	

Table 4. Comparison of cycle-to-cycle error correction slopes among YA, OA, and PWP. Error correction slopes quantify participants' ability to adjust joint-angle errors from one gait cycle to the next, with more negative slopes indicating more effective error correction. Values represent the group mean slopes, calculated from individual participants' slopes, with the group'**s** standard deviation in parentheses. The range indicates the lowest and highest individual slopes within each group, representing the extent of variability in error correction performance. Slopes were computed for the overall Spatial class, the spatial sub-classes (swing (SW), stance (ST), and swing-stance (SWST)), and the six specific SGM patterns, with the sub-class their movement components correspond to (SW Coupe Passe, SW Passe Battement, ST Pique Releve, ST Tombe Heel, SWST Coupe Heel, SWST Attitude Releve). Statistical differences among groups were evaluated using ANOVA (statistical significance of $p < 0.05$), with significant results indicated as follows: *p = 0.026 (SW Coupe Passe), **p = 0.056 (SW), and ***p = 0.034 (spatial). Post-hoc Tukey tests revealed significant pairwise differences specifically between PWP and OA for SW Coupe Passe (*p = 0.008), SW (**p = 0.017), and spatial (***p = 0.010).

Figure 9: Cycle-to-Cycle Correction Slope Box Plot: Spatial Class

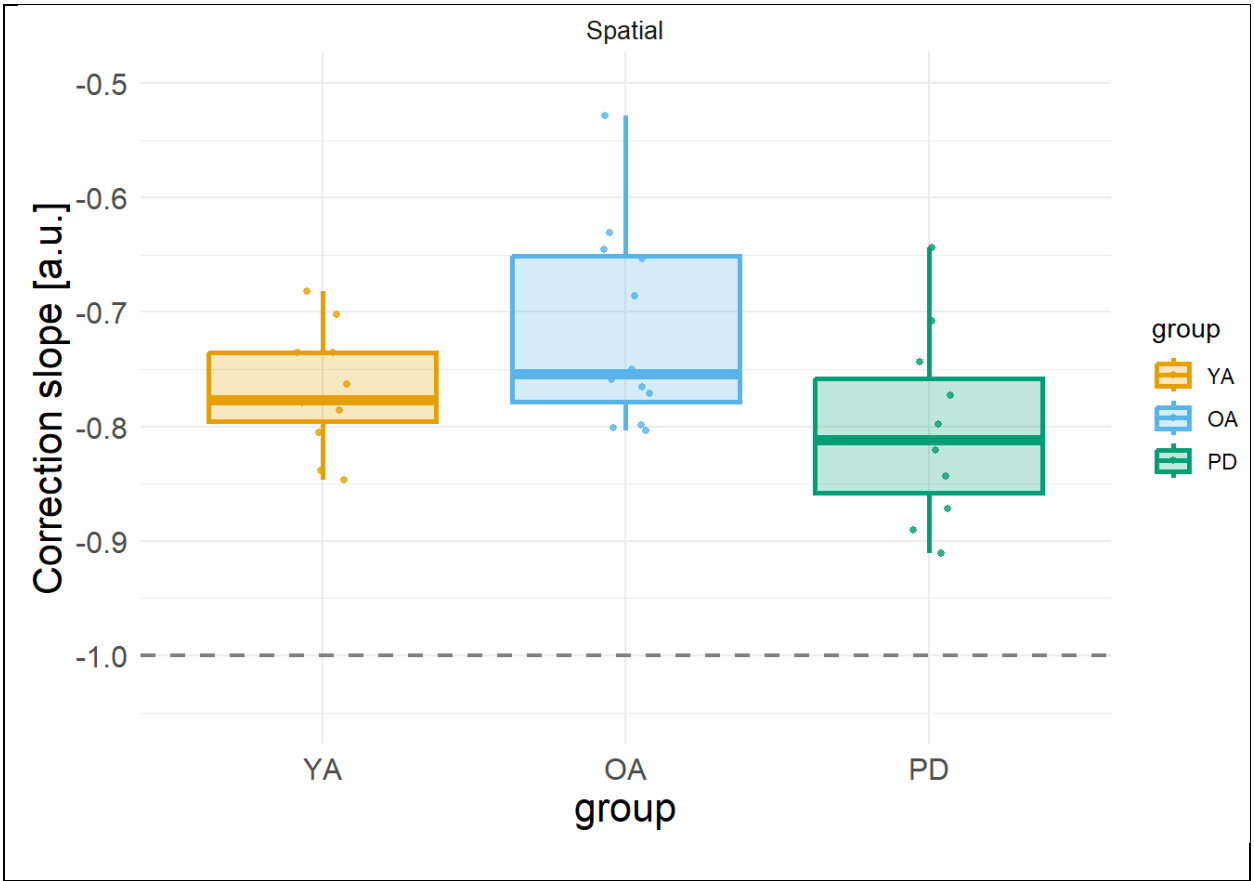


Figure 9. Box plots depicting cycle-to-cycle correction slopes for spatial tasks across YA (yellow), OA (blue), and PWP (green). Values closer to negative one indicates more precise corrections between gait cycles, and values farther from negative one indicates less precise corrections.

Figure 10: Cycle-to-cycle Correction Slope Box Plot: Spatial Sub-Classes

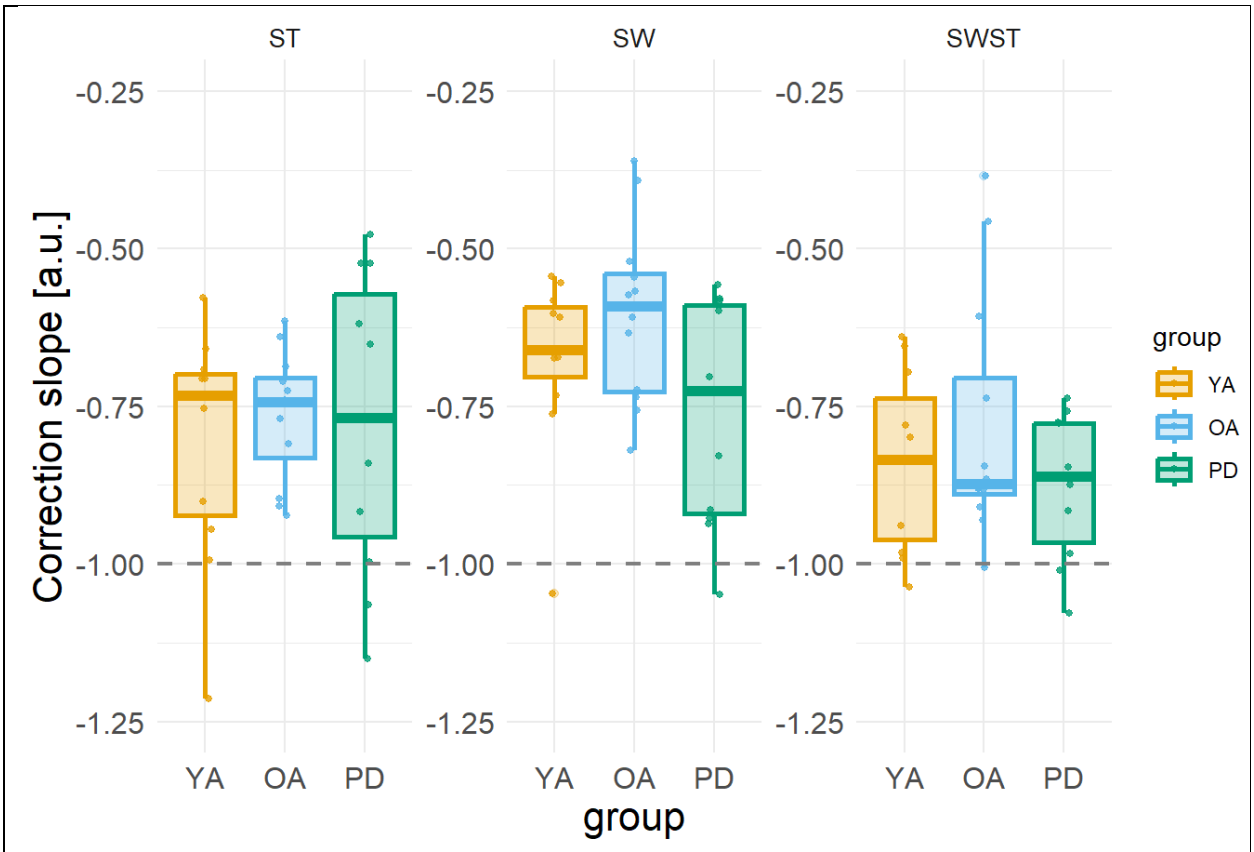


Figure 10. Box plots of cycle-to-cycle correction slopes across stance (ST), swing (SW) and swing-stance (SWST) spatial sub-classes for YA (yellow), OA (blue), and PWP (green). Values closer to negative one indicate more precise corrections between gait cycles, and values farther from negative one indicates less precise corrections.

Figure 11: Cycle-to-cycle Correction Slopes Box Plot: SGM Patterns

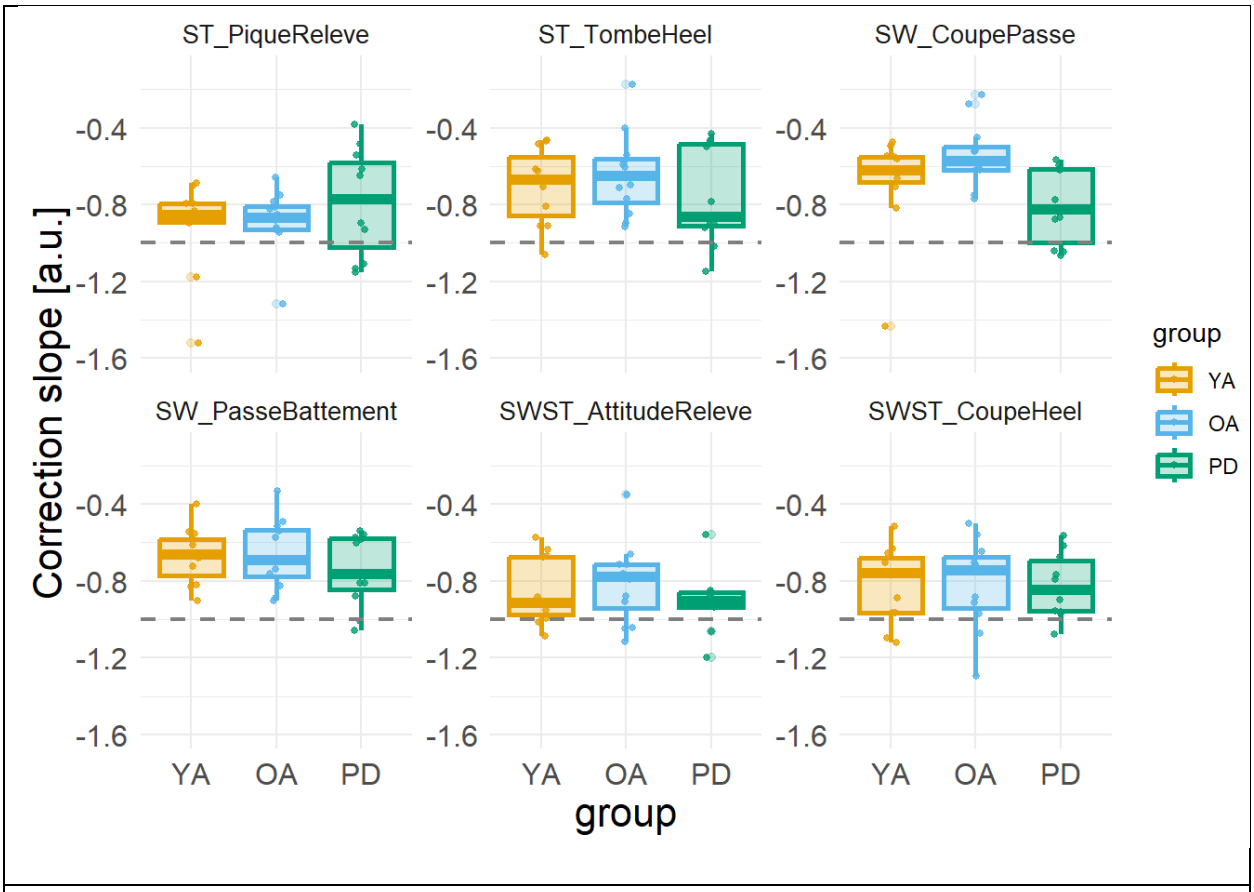


Figure 11. Box plots of cycle-to-cycle correction slopes across all gait modulation patterns within each spatial sub-class of stance (ST), swing (SW), and swing-stance (SWST) for YA (yellow), OA (blue), and PWP (green). Values closer to negative one indicates more precise correction between gait cycles, and values farther from negative one indicates less precise corrections.

Discussion

To my understanding, this is the first study that gathered precision-based data to characterize the effects of PD on kinematic gait modulation beyond aging using an SGM battery. The results are consistent with literature that suggests PD-related deficits on gait variability and cycle-to-cycle adaptability. These findings provide further evidence for swing-phase specific motor impairments for PWP.

SW-Phase Gait Variability and Adaptability in PD: Statistical Findings

The results suggest distinct gait variability and impaired adaptability patterns across populations during swing-phase movements, as measured by standard deviation and cycle-to-cycle error correction slopes. In the mean SD analyses, the significant difference across all groups in passe battement ($p = 0.0018$) within the SW sub-class ($p = 0.0052$) suggests that this specific SGM pattern is a primary contributor to swing-phase variability, which leads to the overarching statistical difference in overall spatial performance ($p = 0.0077$). The significant difference in post-hoc analysis between OA and PWP in passe battement ($p = 0.002$) within the SW sub-class ($p = 0.005$) and overall spatial class ($p = 0.008$) indicate swing-phase movements, specifically passe battement, suggest PD motor pathology may have impacted performance in gait variability among the PWP participants distinctive from aging. Given PWP exhibited significantly greater variability than OA, these findings may correspond to deficits in motor coordination beyond aging during more dynamic movements of gait in individuals with PD. In the cycle-to-cycle error correction analyses, significant differences were found across all populations in swing-phase coupe passe ($p = 0.0105$), swing-phase performance ($p = 0.017$), and overall spatial performance ($p = 0.0105$). The significant difference in post-hoc analysis between OA and PWP in coupe passe ($p = 0.008$) within the SW sub-class ($p = 0.017$) and overall spatial class ($p = 0.010$) indicate swing-phase movements, specifically coupe passe, suggest PD motor pathology may have impacted gait adaptability performance among the PWP participants distinctive from aging. Given coupe passe (a swing phase SGM pattern) showed a significant difference in correction performance across sequential gait cycles for PWP compared to OA, this finding may suggest that PD leads to further difficulty adapting movement patterns across consecutive swing-phase gait cycles. Overall, the statistical analysis findings suggest that swing-

phase movements are disproportionately affected in PWP, both in terms of moment-to-moment variability (SD) and adaptability across cycles.

Clinical Implications of PD SW-Phase Pathology

These findings reveal a disruption in SW-phase motor control processes in people with PD, specifically impairing the reliability and adaptability of gait. To characterize these impairments beyond aging alone, the study applied two precision metrics that quantify deficits in movement predictability and the capacity for corrective adjustments in gait. Precision, as defined in this study, refers to the ability to reproduce joint movements consistently across repeated trials. A key manifestation of reduced precision is increased variability, where joint trajectories fluctuate more trial-to-trial, even when task demands are held constant. The findings demonstrate that people with PD exhibit elevated SW-phase variability, indicating they struggled to reliably execute consistent gait adaptations across repetitions of the same movement sequence. These results also suggest impairments in gait adaptability, meaning individuals with PD are less able to adjust their movements when variability or missteps occur. Together, increased variability and reduced adaptability reflect a broader loss of motor stability, where movements not only lack consistency but also fail to recover effectively when deviations arise. It therefore makes sense that people with PD may exhibit unpredictable foot placements and struggle to navigate complex or unpredictable environments. By combining variability and adaptability metrics within the framework of precision, this study adds nuance to prior findings, suggesting that gait impairments in PD are not solely about achieving a target movement, but also about the reliability of repeated motor execution.

Precision Deficits of SW-Phase: Clinical Findings and Neurological Basis

The findings support existing research indicating that individuals with PD exhibit SW-phase gait impairments. Meta-analyses show that populations with PD have notably shorter SW-phase durations (1.76%) and significantly decreased hip range of motion during the SW-phase (~5.29°) compared to neurotypical groups, with deficits that worsen with increased Hoehn and Yahr severity (Zanardi et al., 2021). Shorter SW-phase durations in people with PD correspond to a shorter step length and a reduced lifting of the foot off the ground (Zanardi et al., 2021). Parkinson, also referred to as shuffling, gait is a common motor pathology that demonstrates the great extent to which SW phase can be compromised in PD (Ataullah, 2024). During shuffling gait, a person with PD experiences a temporarily uncontrolled episode of difficulty walking with extremely small steps in which the feet drag, not fully lifting off the ground (Ataullah, 2024). Shuffling gait serves as both a symptom of increased gait variability and evidence of impaired gait adaptability in PD. A combination of increased motor inconsistency and reduced corrective capacity contributes to a greater risk of tripping or falling, especially when navigating uneven or unpredictable environments (Nascimiento et al., 2021). These deficits in SW-phase precision highlight how PD disrupts the ability to reliably execute the fundamental mechanics of walking, undermining safe and efficient locomotion even in routine or considerably controlled contexts.

Muscular rigidity is a key pathology associated with SW-phase deficits and has specific neurological underpinnings (Johnson et al., 2012). When individuals with Parkinson's are in their ON-time, levodopa is known to effectively reduce rigidity in the limbs (Horak et al., 1996). However, studies suggest it may be less effective at alleviating axial (trunk and neck) rigidity, potentially resulting in persistent gait impairments (Franzen et al., 2009; Wright et al., 2007). Rigidity interfering with adequate foot placement during gait is linked to dysfunctions involving the basal ganglia and deeper brainstem structures, notably the pedunculopontine nucleus (PPN)

and the mesencephalic locomotor region (MLR), both of which regulate axial postural tone (Peterson & Horak, 2016). Animal studies have demonstrated that the MLR plays a significant role in eliciting gait-like flexion and extension of hind-limbs through tonic neural activity (Takakusaki et al., 2013). Meanwhile, the PPN contributes by modulating the inhibition of extensor and flexor alpha motor neurons (Takakusaki et al., 2013). Increased inhibition of these brainstem structures, resulting from basal ganglia dysfunction in PD, compromises the ability to sustain consistent and adaptable motor control. Levodopa's limited efficacy in alleviating axial rigidity may therefore exacerbate lower-limb gait. Consequently, the heightened joint-placement variability and reduced adaptability observed across consecutive gait cycles for PWP are likely due to unresolved neuropathology within these critical brainstem regions.

Limitations

Within the six kinematic plots of each of the SGM patterns performed across each joint (x axis % completion of the cycle and y axis joint angle flexion/dorsiflexion in °), for two participants (one PWP and one YA) erroneous data was found of gait cycles out of distribution within the cycle trend, such as opposing the cycle trend completely (going in opposite direction of the other cycles), or cycles as stagnant lines at joint angle degrees impossible to be performed within the range of motion of the target joint. These participants were excluded from the analysis, resulting in one less participant for each of these groups compared to the OA. Possible sources of error include incorrect use of the OPAL mechanical sensors, which could result in inaccurate kinematic data. For example, if the sensors were positioned incorrectly on the subject, this would produce erroneous joint angle measurements, such as flexion or dorsiflexion values. Additionally, placing the sensors upside down would invert the angle trajectories, further distorting the recorded data.

Future Directions: Enhancing SW-Phase Precision Through Rhythmic and Spatiotemporal Modifications

Emerging research supports the use of dance-based therapies for people with PD, which integrate rhythmic and spatial movement patterns to improve motor-cognitive functioning (Hackney & Earhart, 2009; Bek et al., 2020). These interventions aim to strengthen motor execution, promote adaptability, and reduce gait variability, key deficits identified in this study. An intervention called SpatioTEmporal Activity Modifications (STEAM) is a therapeutic dance program designed by Dr. Hackney's lab to address the unique motor-cognitive challenges in PD by isolating and combining spatial and temporal elements of gait modulation. STEAM draws on established SGM patterns and applies them in structured therapeutic classes for individuals with PD. By separating the spatial and temporal demands of gait in one treatment group (Isolated) and integrating them in another (Coupled), STEAM offers an innovative framework to examine how rhythmic interventions in motor therapy can enhance motor-cognitive rehabilitation, particularly in addressing gait precision deficits common in PD.

Future research should explore how targeted movement interventions like STEAM can be optimized to improve SW-phase precision in individuals with PD. Rhythmic motor control is integral in gait, dance, and therapeutic movement practices, yet its influence on gait variability and cycle-to-cycle movement adaptation remains underexplored. Auditory cueing has been shown to enhance gait initiation, increase step cadence, and lessen the severity of freezing episodes both in clinical and real-world contexts (Howe et al., 2003; Dibble et al., 2004; Rochester et al., 2005); Nieuwboer et al., 2007). One reason auditory cueing benefits people with PD is that it may bypass dysfunctional pathways between the basal ganglia and the supplementary motor area, which typically support internally generated movement signals

(Nieuwboer et al., 1997). Evidence further suggests that auditory stimuli may engage alternative circuits involving the cerebellum and premotor cortex to facilitate movement (Chuma et al., 2006). These mechanisms likely contribute to the success of rhythm-based therapies such as STEAM, which use musical beats to cue movement and may improve gait adaptability in PD populations.

Despite the current structure of STEAM, adjustments to its temporal and spatiotemporal framework could further enhance its therapeutic potential. Currently, STEAM integrates two SGM patterns with two SW-phase components each (Coupe Passe, Passe Battement) and two patterns that target both SW and ST phases (Coupe Heel Strike, Attitude Releve). However, the COU class spatiotemporal setup nor the ISO class temporal setup may not fully accommodate motor limitations common in PD, such as bradykinesia (slowness of movement) (Herz & Brown, 2023). In practice, I observed that executing two SW-phase components in the context of the class, such as transitioning from a Passe to a Battement within pared quick counts (one count per movement), often exceeds the motor capacity of participants with PD, who have trouble generating rapid, controlled actions (Herz & Brown, 2023). These observations reflect the study's findings of impaired SW-phase performance and reduced error correction capacity in PWP. Ensuring an appropriate level of challenge is fundamental in maximizing the effects of motor-cognitive therapy (Guadagnoli & Lee, 2004). I recommend adjusting the STEAM temporal structure by doubling count durations (slows = 4 counts, quicks = 2 counts) to provide participants with additional time to complete gait patterns fully and safely. Temporal adjustments within the ISO class of STEAM would also need to be reflected as well as within the SGM assessment battery used in this cross-sectional study, despite these data not being used in the current analysis. Implementing these modifications may promote more effective motor learning

and improved SW-phase precision performance. Furthermore, future research could investigate whether such rhythmic integration reduce variability and enhance adaptive responses during gait, offering insight into the role of rhythmic structure in facilitating motor precision.

Conclusion

This study identifies SW-phase precision deficits as a key feature of gait impairment in people with PD. Using SGM patterns, I demonstrate that individuals with PD show increased variability and reduced adaptability during SW-phase movement components compared to OA without PD. These findings suggest that impaired movement replicability and recoverability may contribute to instability and fall risk in everyday contexts. This work supports the refinement of rhythm-based dance therapies to enhance gait adaptability and promote more reliable movement in people with PD.

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