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Surface-Dependent Sway Adaptations Reveal Impaired Neuromotor Control in People Living with HIV

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Abstract

Background: People living with HIV (PLHIV) experience balance impairments due to neuropathy, muscle weakness, and central nervous system alterations, which increase fall risk. While most studies focus on level walking, there is limited information about motor control adaptation during gait on inclined surfaces. ***Objective:*** To determine whether postural sway while walking differs between PLHIV at risk of falls and those not at risk during flat and inclined surfaces. ***Methods:*** Thirty-two PLHIV (21 fall risk; 11 non–fall risk) completed walking trials at 0% and 8% incline. The Activities-specific Balance Confidence (ABC) Scale classifies fall risk. Postural sway parameters (RMS and centroidal frequency) were captured with accelerometers. A 2 × 2 mixed MANOVA compared groups and conditions. ***Results:*** A significant main effect of incline was observed ($F(6,25) = 2.980$, $p = .025$, partial $\eta^2 = .417$). Sway RMS and sagittal RMS were greater on level ground than on the incline ($p < .001$). No significant group differences or interactions were found. ***Conclusion:*** Inclined walking reduced sway amplitude while slightly increasing sway frequency, suggesting adaptive neuromuscular control. Incline walking may create a rigid or frizzing postural strategy in PLHIV regardless of fall-risk status. These findings highlight the importance of incorporating environmental challenges into fall-risk assessments and interventions.

Keywords: HIV, postural sway, balance, fall risk, incline walking, motor control.

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INTRODUCTION

Human immunodeficiency virus (HIV) compromises immune function by attacking CD4 white blood cells, rendering the body less able to defend against opportunistic infections and diseases. Once the immune system is weakened, the virus can damage multiple organ systems, including the nervous system, leading to neurological complications. Neurological damage can impair muscular function and contribute to balance alterations and muscle weakness (Yale Medicine, 2024).

HIV also disrupts glial cell function in the brain and triggers inflammation, producing symptoms such as confusion, forgetfulness, and reduced coordination. It may also impair areas of the brain responsible for information processing, thereby hindering the learning of new skills in PLHIV. Clinical presentation in PLHIV often resembles that of individuals with diabetes-related complications (Rosario *et al.*, 2020). For example, Kwon *et al.*, (2002) reported that people with diabetic neuropathy exhibit altered muscle activation patterns during gait compared with matched controls, including differences in gastrocnemius activation timing and peak ankle dorsiflexion. Although the etiology of diabetic neuropathy differs from that of HIV-related neuropathy, both conditions adversely affect balance (Moyle & Sadler, 2012). Importantly, even with antiretroviral therapy, PLHIV remains at elevated risk of peripheral neuropathies due to treatment-related neurotoxicity.

Another common challenge is wasting syndrome due to HIV complications, characterized by a reduction in lean body mass. The Centers for Disease Control and Prevention (CDC) reports that PLHIV lose, on average, at least 10% of their baseline body weight. Muscle loss significantly affects gait and balance due to altered sensory and motor integration (Rosario MG,

2023) and can impair daily function (Dudgeon, 2006). Muscle mass also creates a reduction and further compromises functional abilities such as single-leg balance. Fama et al. (2007) found that PLHIV exhibit impaired single-leg stance, particularly with eyes closed, indicating that balance deficits are multifactorial.

In the same vein, weakness of the quadriceps and gluteal muscles may be a primary contributor to these balance and gait issues, as several studies suggest. In those living with HIV, performance on the five-time sit-to-stand test (5TSTS) falls within normal limits, whereas others indicate prolonged completion times (Bauer *et al.*, 2011; Richert *et al.*, 2011). These inconsistencies suggest that, first, the quadriceps could be weakened by muscle reduction, and second, the effects of HIV on neuromuscular function are heterogeneous and not linear, leading to individuals experiencing complications at different stages of the condition.

Despite more than four decades of research, falls remain a pressing concern in PLHIV (Saylor *et al.*, 2018). Structural and functional changes to muscle, vestibular systems, and proprioception collectively contribute to balance impairments, often manifesting as increased center-of-pressure excursions and altered balance strategies (Berner *et al.*, 2017; Rosario *et al.*, 2020; Ruiz *et al.*, 2013). The mechanisms underlying kinematic alterations remain incomplete. It is unclear whether specific balance variables are more affected than others or whether early deviations in sway dynamics could predict fall risk. Addressing these gaps, the present study examined whether postural sway differs between PLHIV at risk of falls and those not at risk when walking on flat versus inclined surfaces (Amiro *et al.*, 2025; Berner *et al.*, 2017).

Based on the above, we hypothesized that there would be no significant differences in postural sway between fall-risk and non–fall-risk groups during level-ground walking. However, given the additional demands of inclined walking, we postulated that sway differences would emerge under inclined conditions.

METHODS

This retrospective observational study was conducted in 2023 at La Perla de Gran Precio (LPGP), a nonprofit organization that serves PLHIV in San Juan, Puerto Rico. The study adhered to all privacy and confidentiality standards established by LPGP and was approved by the Texas Woman's University Institutional Review Board (IRB #FY2023-169).

A total of 35 participants were recruited using convenience sampling. Inclusion criteria were: (1) diagnosis of HIV, (2) age between 18 and 65 years, (3) current participation in an antiretroviral therapy protocol, and (4) orientation to time, place, and space. Exclusion criteria included: requirement of an assistive device to ambulate, unstable angina or myocardial infarction within the past month, pregnancy, or history of hospitalization, musculoskeletal injury, or surgery within the previous six months.

Procedures

Following written informed consent, demographic information was collected. Participants then completed the Activities-specific Balance Confidence (ABC) Scale to assess perceived balance confidence and fall risk. Although initially designed to measure balance confidence, the ABC Scale has been validated as a fall risk assessment tool across populations such as PLHIV, Parkinson's disease, and post-stroke (Beninato *et al.*, 2009; Erlandson *et al.*, 2019; Mak & Pang, 2009; Powell & Myers, 1995). Prior work indicates that PLHIV individuals scoring ≤80% are likely to experience multiple falls over two years (Erlandson *et al.*, 2019). Therefore, this study used a cut-off score of 80% or lower to categorize fall risk. Both English and Spanish versions of the scale were available.

After completing the ABC Scale, participants were fitted with the Mobility Lab APDM system. Six inertial sensors were used and placed at the following anatomical sites: (1) dorsal aspect of the midfoot bilaterally, (2) wrists bilaterally, (3) manubriosternal joint, and (4) lumbar spine at the L5 vertebra.

Participants first performed a Six-Minute Walk Test (6MWT) to determine average gait speed for treadmill testing. For those unable to complete six minutes, gait speed was estimated from the distance covered in two minutes. After the 6MWT, participants rested for five minutes before completing a two-minute treadmill warm-up at 0% incline. They were then instructed to walk 7 meters (as measured by Mobility Lab) at their preferred gait speed, determined by the 6MWT. Data collection began immediately following the warm-up.

Each participant performed two trials at two incline conditions: 0% and 8%. The 8% incline was selected to approximate the Americans with Disabilities Act (ADA) standard for ramp grade (Handi Ramp, 2022). Participants rested for one minute between trials. Testing was terminated if participants reported chest or lower extremity pain, dizziness, or requested to stop.

During the walking trials, the Mobility Lab APDM system collected postural sway measures along with gait data. The following parameters were extracted:

- Postural sway RMS – root mean square of sway in both coronal and sagittal planes
- Postural sway RMS (coronal) – root mean square of sway angle in the coronal plane
- Postural sway RMS (sagittal) – root mean square of sway angle in the sagittal plane

- Centroidal frequency – frequency of sway from the centroid of the sway path's power spectrum in the transverse plane
- Centroidal frequency (coronal) – frequency of sway from the centroid of the sway path's power spectrum in the medial-lateral direction
- Centroidal frequency (sagittal) – frequency of sway from the centroid of the sway path's power spectrum in the anterior-posterior direction

Statistical Analysis

Before analysis, ABC scores were calculated, and participants were divided into two groups: fall risk and non–fall risk. Participants who scored ≤80% on the ABC Scale were categorized as fall risk, whereas those who scored >80% were classified as non–fall risk. Descriptive statistics were used to summarize demographic characteristics, and independent t-tests were conducted to compare demographics between groups.

The primary objective of this study was to examine whether postural sway measurements differed between PLHIV at risk for falls and those not at risk, under two walking conditions (0% and 8% incline). A 2 × 2 mixed MANOVA was performed to compare the two groups (fall risk vs. non–fall risk) across the two levels of inclination. Statistical significance was set at $p \leq .05$.

RESULTS

Thirty-five participants were recruited; however, only 32 completed all testing. Two participants withdrew for personal reasons, and one was excluded due to treadmill weight restrictions at the nonprofit facility.

Group Distribution. Table 1 presents demographic characteristics by group. Of the 32 participants, 21 were classified as fall risk (ABC ≤80%), and 11 were classified as non–fall risk (ABC >80%). An independent t-test revealed a significant difference in ABC scores between groups ($p = .006$).

Postural Sway and Frequency. Table 2 displays descriptive statistics for postural sway and centroidal frequency variables. A 2 × 2 mixed MANOVA was conducted to examine differences across group and incline conditions (Table 3). Results demonstrated a significant main effect for level of inclination, $F(6,25) = 2.980$, $p = .025$, partial $\eta^2 = .417$. There was no significant main effect for fall risk, $F(6,25) = 1.527$, $p = .210$, partial $\eta^2 = .268$, and no significant interaction between fall risk and inclination, $F(6,25) = 1.158$, $p = .359$, partial $\eta^2 = .218$.

Univariate Analysis. Follow-up univariate ANOVAs were performed to further explore the significant main effect of inclination across the six outcome variables. Results showed no significant interaction or main effect for fall risk; however, there was a significant main effect of inclination for postural sway RMS ($p < .001$) and postural sway RMS sagittal ($p < .001$). Pairwise comparisons revealed that both postural sway RMS ($p < .001$) and postural sway RMS sagittal ($p < .001$) were significantly greater on flat ground compared to inclined walking, regardless of fall risk classification (Table 4).

No significant differences were observed for postural sway RMS coronal ($p = .164$), centroidal frequency ($p = .474$), centroidal frequency coronal ($p = .579$), or centroidal frequency sagittal ($p = .059$). Nonetheless, a trend was noted in which centroidal frequency values were consistently greater at 8% incline compared to 0%, whereas postural sway values were consistently greater at 0% incline compared to 8%.

Table 1: Demographic data of all participants

	Non-fall risk (n=11)	Fall risk (n=21)	Independent t-test
Age (yrs)	57.09 +/- 13.019	60.52 +/- 6.570	p=.066
Years with diagnosis	22.45 +/- 9.720	26.19 +/- 8.448	p=.652
CD4 count (cells per cubic millimeter)	824.00 +/- 314.296	696.00 +/- 233.586	p=.109
Gait speed (m/s)	.748 +/- .105	.756 +/- .138	p=.109
Body Mass Index	27.321 +/- 5.728	26.743 +/- 5.916	p=.937
ABC Scale Scores	90.741 +/- 6.547	61.772 +/- 24.392	p=.006

Table 2: Descriptive Statistics for Postural Sway and Centroidal Frequency Variables During Flat, Even Walkway

	Non-Fall Risk (n=11)	Fall Risk (n=21)
Centroidal Frequency (Hz)	2.270	2.111
Centroidal Frequency- Coronal (Hz)	1.378	1.536
Centroidal Frequency- Sagittal (Hz)	1.778	1.749
Postural Sway RMS	1.061	1.065
Postural Sway RMS- Coronal	.638	.634
Postural Sway RMS- Sagittal	.816	.833
Centroidal Frequency (Hz)	2.281	2.154
Centroidal Frequency- Coronal (Hz)	1.332	1.632

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	Non-Fall Risk (n=11)	Fall Risk (n=21)
Centroidal Frequency- Sagittal (Hz)	1.833	1.851
Postural Sway RMS	1.001	.989
Postural Sway RMS- Coronal	.629	.583
Postural Sway RMS- Sagittal	.756	.780

Descriptive Statistics for Postural and Frequency Measures at Different Inclines

Note. Values represent the mean centroidal frequency (Hz) and postural sway root mean square (RMS) measures across 0% and 8% incline conditions. Centroidal frequency and RMS values are presented for overall, coronal, and sagittal planes to illustrate directional changes in postural control with incline variation.

Note. This table presents mean values for centroidal frequency and postural sway root mean square (RMS) among participants classified as non-fall risk (n = 11) and fall risk (n = 21) during flat, even walkway conditions. The significance level was set at $p \leq .01$

Table 3: Repeated Measures Multivariate Analysis of Variance (MANOVA)

	F Value	Df	P Value	Partial eta η2
Fall risk	1.527	6	.210	.268
Level of inclination	2.980	6	.025	.417
Fall risk * Elevation	1.158	6	.359	.218

Note. This table presents the results of the repeated measures MANOVA examining the effects of fall risk, level of inclination, and their interaction on the dependent variables. The level of inclination showed a significant main effect ($p = .025$, $\eta^2 = .417$), whereas fall risk and the fall risk × elevation interaction were not statistically significant.

Table 4: Pairwise Comparisons for the Level of Inclination

Measure	Comparisons	Mean Difference	Std. error	P value
Centroidal frequency	0% vs 8% incline	-.027	.037	.474
Centroidal frequency-coronal	0% vs 8% incline	-.025	.044	.579
Centrodial frequency sagittal	0% vs 8% incline	-.079	.040	.059
Postural sway RMS	0% vs 8% incline	.068	.018	<.001*
Postural Sway RMS coronal	0% vs 8% incline	.029	.021	.164
Postural Sway RMS- Sagittal	0% vs 8% incline	.056	.015	<.001*

Note. This table summarizes the pairwise comparisons between 0% and 8% treadmill inclinations across centroidal frequency and postural sway measures. Values represent the mean difference, standard error, and associated p values for each variable. An asterisk (*) indicates a statistically significant difference ($p < .05$).

DISCUSSION

This study aimed to elucidate how surface inclination affects postural sway (amplitude and frequency) across PLHIV differing in fall risk. PLHIV consistently exhibits gait and balance impairments—comparable to those seen in similar age brackets —despite effective antiretroviral therapy, likely due to multisystem HIV complications. However, most balance research in HIV has centered on level-ground assessments, leaving the impact of real-world perturbations like incline surfaces underexplored. By incorporating both RMS sway and centroidal frequency (CM) measures, this study helps bridge that gap and explores adaptive postural strategies among PLWH. RMS sway represents the movements the body has during standing motor control. Similar to sway, the higher the score, the more the subject shows instability. On the other hand, CM indicates whether sway or balance exhibits rapid movements (correction) or slow, controlled shifts in movements (Prieto *et al.,* 1996; Voss *et al.,* 2021).

Our results demonstrated significantly higher postural sway (total RMS and sagittal RMS) on level surfaces compared to an 8% incline, with centroidal frequency trending upward, though not considerably, on the incline. This unexpected pattern suggests inclines may prompt stabilization via compensatory neuromuscular strategies, such as increased stiffness or altered muscle activation control. The data partially support the hypothesis that slopes affect postural dynamics, although not in the expected direction. Additionally, the absence of significant effects for fall risk group or group-by-inclination interactions indicates that both PLWHIV with and without risk of falls employed similar adaptive mechanisms to maintain balance under incline conditions.

However, some research suggests that a reduction in CM values indicates a rigid or stiffness strategy to compensate for the reduced stability (Duarte & Freitas, 2010; Alkathiry, 2025). This study's discoveries enhance existing understanding of balance impairments in HIV by showcasing context-dependent sway responses. To further elucidate this point, prior systematic reviews show that PLWH experience increased center-of-pressure excursions and slowed gait, particularly under challenging conditions. The reduction in sway on an incline may reflect heightened neuromuscular engagement in response to perceived

environmental factors. The previous statement is consistent with models of postural control involving regulation of muscle tone and equilibrium adjustments. Additionally, emerging work indicates that people with asymptomatic HIV demonstrate multi-directional sway increases even before clinical fall onset, tied to sensory integration deficits, neuromuscular alterations, vestibular involvement, prolonged reaction time, and motor cortex changes, to name a few (Rosario *et al.*, 2022). The statement above underscores the idea that slope-induced adaptations might uniquely evoke control strategies not captured by level-surface testing.

As a note, the modest sample size potentially could have limited statistical power, particularly for detecting subtle frequency-domain effects or interaction patterns. Nevertheless, the pool sample collected reflects a proper region of the metropolitan area in Puerto Rico. Secondly, although the chosen slope represents a standard sidewalk slope, the current study evaluated a single slope (8%), restricting extension to steeper or less steep angles. Notably, we did not characterize participants by HIV-related components such as neuropathy severity, antiretroviral regimen, cognitive impairment, or structural brain changes, all of which may influence sway dynamics. Finally, the controlled laboratory environment lacks ecological complexity, such as fatigue, dual-task demands, and environmental distractions that commonly affect postural stability in daily life. Nevertheless, a treadmill is an excellent equipment found in different facilities such as rehab clinics and fitness centers, making our selection and data collection area reproducible.

Future studies should enroll well-characterized HIV cohorts differentiated by neuropathy status, neurocognitive function, treatment regimen, and neural structural changes. Exploring a spectrum of incline levels and incorporating dynamic, dual-task, or fatigue protocols would bridge a correlation to multiple real-life scenarios and thus enhance ecological validity. Complementary measures such as electromyography (EMG) could clarify neuromuscular strategies underpinning decreased sway on slopes. Techniques such as time–frequency EMG analyses may provide novel insights into muscle co-contraction and control dynamics during balance perturbations. Finally, field-based assessments—real-world walking, indoor/outdoor contexts—could better capture the everyday balance responses of PLHIV.

CONCLUSION

The current study illustrates that surface inclination influenced postural control in PLHIV. Specifically, sway amplitude decreased, while sway frequency demonstrated a tendency to increase, when participants walked at an 8% incline compared to level ground. These findings counter the common assumption that sloped surfaces inherently heighten instability or movements paired with fall risk, particularly in PLHIV. Instead, the results suggest that incline walking may stimulate stabilizing neuromuscular adaptations, potentially provoking a stiffness or freezing strategy under more challenging environmental conditions. By highlighting inclination as a modifiable and underexplored variable, this study contributes to a more nuanced understanding of adaptive postural strategies in individuals with HIV-associated balance impairments. Furthermore, the results underscore the importance of expanding fall risk assessment and intervention paradigms to include real-world challenges beyond level ground walking.

Taken together, these findings provide preliminary evidence that incline walking may activate compensatory control mechanisms that reduce sway amplitude, even among individuals traditionally affected by balance instability. This has important implications for rehabilitation and community mobility, suggesting that therapeutic strategies incorporating controlled incline walking may help strengthen adaptive balance responses. Ultimately, this study sets the stage for future investigations to refine intervention approaches, validate these findings across larger and more diverse cohorts, and explore how environmental conditions can be leveraged to mitigate fall risk in real-world scenarios.

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