World Neurosurgery: X 22 (2024) 100299

Contents lists available at ScienceDirect

World Neurosurgery: X

journal homepage: www.journals.elsevier.com/world-neurosurgery-x

Utilizing kinematic analysis of postural instability as an objective measure to aid in distinguishing between normal pressure hydrocephalus and Parkinson's disease

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ARTICLE INFO

Keywords:
Normal pressure hydrocephalus
Postural instability
Kinematics
Diagnosis
Parkinson's disease

ABSTRACT

Objective: Patients with normal pressure hydrocephalus (NPH) and Parkinson's Disease (PD) can clinically appear quite similar at baseline evaluation. We sought to investigate the use of kinematic assessment of postural instability (PI) using inertial measurement units (IMUs) as a mechanism of differentiation between the two disease processes.

Methods: 20 patients with NPH, 55 patients with PD, and 56 age-matched, healthy controls underwent quantitative pull test examinations while wearing IMUs at baseline. Center of mass and foot position data were used to compare velocity and acceleration profiles, pull test step length, and reaction times between groups and as a function of Unified Parkinson's disease Rating Scale Pull Test ($UPDRS_{PT}$) score.

Results: Overall, the reactive postural response of NPH patients was characterized by slower reaction times and smaller steps compared to both PD patients and healthy controls. However, when patients were grouped by $UPDRS_{PT}$ scores, no reliable objective difference between groups was detected.

Conclusion: At their initial evaluation, very few NPH patients demonstrate "normal" or "mild" PI as they appear to be older upon presentation compared to PD patients. As a result, kinematic assessment utilizing IMUs may not be helpful for differentiating between NPH and PD as a function of $UPDRS_{PT}$ score, but rather as a more fine-tuned method to define disease progression. We emphasize the need for further evaluation of incorporating objective kinematic data collection as a way to evaluate PI and improve patient outcomes.

1. Introduction

Parkinson's disease (PD) is one of the most common neurodegenerative diseases and affects nearly 60,000 people per year.[1] Patients with normal pressure hydrocephalus (NPH), often characterized as a type of parkinsonism, are underdiagnosed and undertreated, and typically present with a classical triad of gait, cognitive, and urinary symptoms, making differentiating between the two diagnoses difficult.[2] Postural instability, or the inability to maintain an upright posture given a perturbation or change in environment, is a clinical feature present in both PD and NPH and can significantly decrease quality of life and increase mortality within these patient groups.[3,4] A recent study demonstrated NPH patients have increased mortality compared to healthy adults which can be significantly improved when NPH patients improve their gait after shunt surgery,[5,6] indicating the importance of improving motor symptoms as a measure for increased survival. Furthermore, this

Abbreviations: NPH, normal pressure hydrocephalus; PD, Parkinson's disease; PI, postural instability; IMU, inertial measurement units; $UPDRS_{PT}$, Unified Parkinson's disease rating scale pull test; Mini-BEST, Mini- Balance Evaluation Systems Test; MVAHCS, Minneapolis VA Health Care System; UMN, University of Minnesota; LDT, lumbar drain trial; UBACC, University of San Diego Brief Assessment of Capacity to Consent; MDS-UPDRS, Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale; COM, center of mass; V_{COM}, center of mass velocity; A_{COM}, center of mass acceleration; VPS, ventriculoperitoneal shunt; DBS, deep brain stimulation; LSVT-BIG, Lee Silverman Voice Training-BIG.

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https://doi.org/10.1016/j.wnsx.2024.100299
Received 7 April 2023; Accepted 20 February 2024
Available online 25 February 2024

increased fall risk is associated with an increased risk for other injuries, including hip fracture, for both PD and NPH patients.[5,6] Traditionally, gait and postural instability are measured with ordinal rating scales, such as the Unified Parkinson's disease rating scale pull test ($UPDRS_{PT}$) and Mini- Balance Evaluation Systems Test (Mini-BEST).[7,8] However, these evaluations produce highly variable and subjective results depending on the provider,[9] making it difficult to ascertain surgical candidacy and the potential benefit of surgical intervention for these patients.

Alternatively, previous work has identified a quantitative kinematic system of evaluation as both efficient and more objective in measuring gait and postural instability.[9] With this method, patients are equipped with inertial measurement units (IMUs) and are examined with purposely varied pull intensities (i.e., a spectrum from very easy pulls to very hard pulls). This kinematic approach to evaluating postural instability theoretically reduces inter-provider variability by quantifying the inherent variability in the exam maneuver and provides more objective insight into a patient's disease process. Furthermore, given the improved consistency and repeatability of these data, there is the potential for using quantitative kinematics in baseline pre-surgical evaluation for these patients. Currently, there is little research on whether postural instability among patients with NPH and PD at baseline can be differentiated based on their kinematic profiles. Given their overlapping symptom profiles, utilizing quantitative kinematic assessment could be useful as a diagnostic tool.

In this study, we sought to investigate postural instability among patients with NPH and PD compared to age-matched healthy controls as a mechanism for differentiating between patient groups in a clinical setting. Specifically, we sought to examine existing baseline deficits and the relationship between center of mass (COM) velocity profile and stride length, pull intensity, and reaction time during the clinical pull test using well-established quantitative kinematic analysis.

2. Methods

2.1. Subjects

Twenty NPH patients, 55 PD patients, and 56 age-matched control participants were enrolled over a period of three years from the Minneapolis VA Health Care System (MVAHCS) and University of Minnesota (UMN) in a prospective cohort study design. Control participants had unimpaired gait and balance with no prior clinical diagnosis of a neurological disorder affecting movement or perception of movement. Data from movement disorder participants were taken from baseline testing sessions as part of surgical evaluations. Specifically, NPH patients with gait/balance dysfunction, cognitive impairment, urinary incontinence in addition to ventriculomegaly out of proportion with cortical atrophy were diagnosed with possible or probable NPH based on standard criteria by a movement disorders neurologist.[10] They were then evaluated with three-day lumbar drain trial (LDT) where they underwent quantitative kinematic, physical therapy and neuropsychological testing pre- and post-LDT. For the purposes of this study, all data included from patients with NPH were from pre-LDT evaluations. PD participants who were clinically diagnosed by a movement disorders neurologist using Movement Disorders Society clinical diagnostic criteria[11] undergo ON/OFF motor testing during deep brain stimulator surgical evaluations. For the purposes of this study, all data included from patients with PD were from OFF dopaminergic medication evaluations. Potential participants were excluded if they did not have the capacity to consent as identified by the University of San Diego Brief Assessment of Capacity to Consent (UBACC) or if they had a comorbidity that affected their gait or balance. We collected relevant demographic information (see Table 1) from each patient as well as their responses to several questionnaires related to their balance and falls.

Table 1
Patient demographics and postural response variables.

Demographic:	Patient Group		
	NPH	PD	Control
Sex	*17 M, 3 F*	*44 M, 11 F*	*18 M, 38 F*
***Weight* in *kg* (SD)**	*89.46 (20.63)*	*89.63 (19.27)*	*75.64 (16.51)*
***Age* in *years* (SD)**	*72.40 (7.21)*	*64.89 (8.30)*	*63.52 (6.00)*
***Height* in *cm* (SD)**	*172.56 (10.10)*	*177.57 (9.84)*	*169.24 (11.00)*
$UPDRS_{PT}$ pull-test score (SD)	*1.65 (0.875)*	*0.909 (1.16)*	*0.161 (0.371)*
Duration of disease in years (SD)	0.375 (0.293)	7.37 (4.06)	– –

2.2. Data collection

All NPH patients underwent kinematic assessment before starting the LDT. All PD patients underwent kinematic assessment initially after being OFF dopaminergic medication for 12 h for baseline evaluation as part of ON/OFF motor testing, part III of Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS). Both groups of patients were also tested after intervention (LDT and dopaminergic medication) but these results are not reported here as this study was specifically designed to examine baseline differences in the groups. Healthy age-matched controls were evaluated for baseline kinematics only. This study was approved by the MVAHCS and UMN Institutional Review Boards (IRB) and all participants provided informed consent for participation.

NPH patients participated in 20 baseline sessions with a mean of 15.1 pull test trials per session, for a total of 306 trials across patients. PD patients participated in 55 baseline sessions with a mean of 13.47 pull test trials per session, for a total of 740 trials across patients. The healthy age-matched control participants participated in 56 evaluation sessions with a mean of 14.79 pull test trials per session, for a total of 827 trials across subjects. Regarding demographic information (see Table 1), we saw differences in sex between patients with NPH compared to PD and compared to age-matched control subjects (most NPH patients we saw at baseline were Veterans and therefore men).

2.3. Task details

All participants were fitted with a set of 15 inertial measurement units (IMUs; Xsens, Enschede, Netherlands) recording at 60 Hz during each kinematic session evaluating gait and postural instability (Supplemental Fig. 1). Body limb segments (cm) for each patient were measured at their baseline session. To assess postural instability, a trained clinical examiner followed the instructions on the MDS-UPDRS form for conducting the pull test[3] and conducted between 10 and 20 pull test trials for each patient. The pull test involves a perturbation wherein the participant is pulled backwards at the shoulders to induce a reactionary step response to regain stability and prevent from falling. The examiner used clinical discretion to determine the force of the induced perturbation during the recorded trials, but they were instructed to use an unpredictable variety of intensities throughout the trials as able. The first trial after the instructional trial was scored in the standard manner on the MDS-UPDRS scale. This is scored as "0—normal"; "1—slight"; "2—mild"; "3—moderate"; "4—severe": very unstable.

2.4. Data extraction

A three-dimensional biomechanical model is created for each patient based on limb segment inputs and sensor orientation.[12] Center of mass (COM) and foot position data were exported from the recorded motion capture analysis file and imported and analyzed within Igor Pro 6.00 to calculate velocity and acceleration for the COM and foot position. Relevant data points were verified via timestamps being

cross-referenced in Visual 3D and clinical video (Supplemental Figs. 1 and 2). Data were then exported into R (v 2022.12.0 + 353) and analyzed using custom scripts.

2.5. Statistical analysis

The purpose of this study was to assess the potential for kinematic assessment of postural instability to delineate patients with NPH from patients with PD. We first compared postural responses between NPH patients, PD patients, and healthy controls. In addition, we wanted to investigate how the postural responses of patients with PD compared to those of patients with NPH and healthy, age-matched controls who received the same MDS-UPDRS score. Once the relevant kinematic points were identified and variables calculated as described above, we first grouped patients by disease and then by $UPDRS_{PT}$ score and subsequently performed statistical testing described below.

An individual's postural response to any given pull test can be determined using COM velocity (V_{COM}). A "normal" response usually shows a sharp rise to a peak value as the participant is pulled backwards at the shoulders, a sharp decrease in V_{COM}, showing the participant recovering from the pull with one to two steps (Supplemental Fig. 2). However, an "abnormal" response usually shows a less steep rise to the peak value and a shallower decrease in V_{COM}, indicating the participant reacts slower and takes more steps to recover from the pull. Two critical variables to evaluate the postural response are the initial step length and reaction time to the initial pull backwards.[8] Initial step length is defined as the difference in foot position between the initial step onset and land, while reaction time is defined as the time between the perturbation onset of the pull backwards and the initial first step (Supplemental Fig. 2). Furthermore, we examined the reaction foot velocity, defined as the foot which first moved from the starting position in response to the retropulsion of the pull test, in addition to overall V_{COM}. Statistically significant differences in V_{COM} plots were considered to be non-overlapping 95% confidence intervals of timeframes 50 ms or greater.[9]

Prior research has shown pull intensity (measured by COM acceleration backwards before the initial step) affects both step length and reaction time during the pull test.[9] Thus, linear mixed-effects models were created to analyze mean differences of step length and reaction time between groups, adjusting for the effects of pull intensity. A Bonferroni correction was applied to all p values for all statistical comparisons to correct for multiple group comparisons. Group differences in step length and reaction time were evaluated via mixed effects with p-values less than 0.05 to be considered statistically significant after Bonferroni correction.

3. Results

3.1. Overall kinematic profile

Patients with NPH evaluated at baseline ($n = 20$, trials = 306) in this study were more likely to be male, older, and present with more severe postural instability (seen by an increased $UPDRS_{PT}$ score) compared to patients with PD ($n = 55$, trials = 740) and their healthy age-matched controls ($n = 56$, trials = 827) (Table 1).

Fig. 1A demonstrates COM velocity (V_{COM}) profiles for each group. Control participants reached the highest peak V_{COM} values (~60 cm/s) with PD participants reaching intermediate values (~40 cm/s) and NPH participants reaching the lowest V_{COM} (~30 cm/s). Because COM velocity is heavily influenced by how hard the patient is pulled backwards (as represented by peak COM acceleration prior to the initial step backwards; A_{COM}), we corrected for the strength of this postural perturbation (pull intensity) in our linear mixed effects models. After this correction, PD participants still had statistically significantly lower peak V_{COM} values compared to control participants ($p = 0.04$), and higher peak V_{COM} than NPH participants ($p < 0.001$). NPH participants had lower peak V_{COM} values compared to both PD ($p < 0.001$) and controls ($p < 0.001$). Similarly, PD participants demonstrated significantly slower reaction foot peak velocity than healthy controls ($p < 0.001$) but higher reaction foot velocity than NPH participants ($p < 0.01$). NPH participants again had lower reaction foot peak velocities compared to both controls ($p < 0.001$) and PD patients ($p < 0.01$).

As expected, the V_{COM} profiles for each group implied that both NPH and PD participants were less able to successfully respond to a pull backwards compared to controls. To determine the manner in which their postural instability manifested, we examined two important

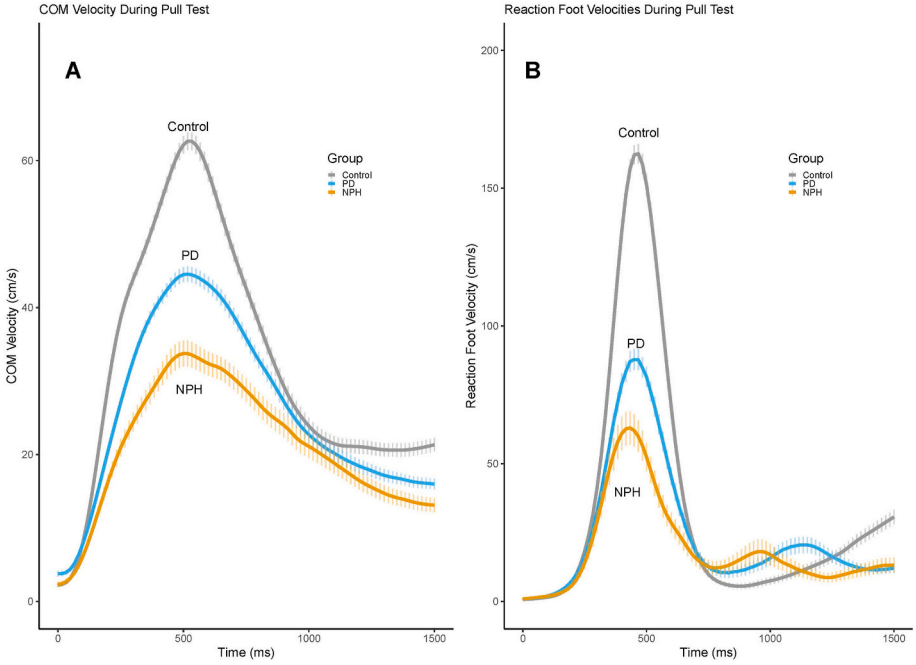

Fig. 1. A. Kinematic pull test outcomes for mean V_{COM} over time and **B**. Mean reaction foot velocity over time grouped by patient population (age-matched control subjects, PD, and NPH).

kinematic parameters previously demonstrated to be linked to a successful postural response,[9] reaction time and initial step length. Fig. 2A and B shows that both PD and NPH participants reacted slower ($p < 0.001$, $p < 0.001$, respectively) and took smaller initial steps ($p < 0.001$, $p < 0.001$, respectively) than age-matched controls. Again, similar to the pattern seen with V_{COM}, we found that control participants had the fastest reaction time at ~250 ms with PD at intermediate values and NPH participants reacting the slowest, though there was not a statistically significant difference in reaction time between PD and NPH participants after controlling for pull intensity ($p = 0.07$). Control participants also took the largest steps ($p < 0.001$ vs. PD and NPH) with PD participants taking smaller steps ($p < 0.001$ vs. controls, $p < 0.01$ vs. NPH) and NPH participants taking the smallest steps ($p < 0.001$ vs. controls, $p < 0.01$ vs. PD).

We purposely varied the pull intensity because a patient's reaction time and step length changes depending on pull intensity.[9] In general, reaction time decreases and step length increases as pull intensity increases. Interestingly, the pattern of reaction time scaling differed between groups. Healthy control participants had essentially zero slope, meaning they reacted similarly fast for an easy or a hard pull, without any scaling to pull intensity (Fig. 2C) with increasingly larger slopes for PD and NPH participants, respectively. Only the NPH and Control groups had statistically different reaction time slopes (Fig. 2C, $p = 0.038$) such that PD participants were statistically indistinguishable from either NPH or controls in terms of scaling their reaction time to pull intensity. The *y*-intercept values of these linear models represents the reaction time for a given pull backwards and NPH participants demonstrated statistically significantly larger y-intercepts compared to both PD ($p < 0.001$) and controls ($p < 0.001$). Again, PD participants were statistically indistinguishable from healthy controls in terms of reaction time *y*-intercept values (Fig. 2C, $p = 0.10$).

When we looked at initial step length throughout the full range of pull intensities (Fig. 2D), a different pattern emerged. All groups had very a similar step scaling response to pull intensity (slope) with no differences between groups in terms of step length slope. There were significant differences in the y-intercepts between groups, however, with step length curves essentially shifted up for each group (Fig. 2D). Control participants took the largest step for a given pull (largest *y*-intercept) compared to both PD ($p < 0.001$) and NPH ($p < 0.001$) participants while there was no difference in y-intercepts between PD and NPH participants. Thus, all groups scaled their initial step length to pull intensity backwards in a similar fashion while control participants took larger steps overall compared to both groups.

3.2. *Postural instability in patients with NPH as a function of $UPDRS_{PT}$ score*

Because the NPH patients in this study presented with more severe symptoms, we were next interested in determining whether their kinematic profiles were truly different from healthy controls and PD patients or whether these differences reflected differences solely in severity of disease. In order to do that, we compared all three groups as a function of $UPDRS_{PT}$ score. It is important to note that very few patients with NPH presented at baseline testing with a score of "0", representing "normal" postural instability and therefore comparisons with this group are limited by sample size. Also, there were no age-matched healthy

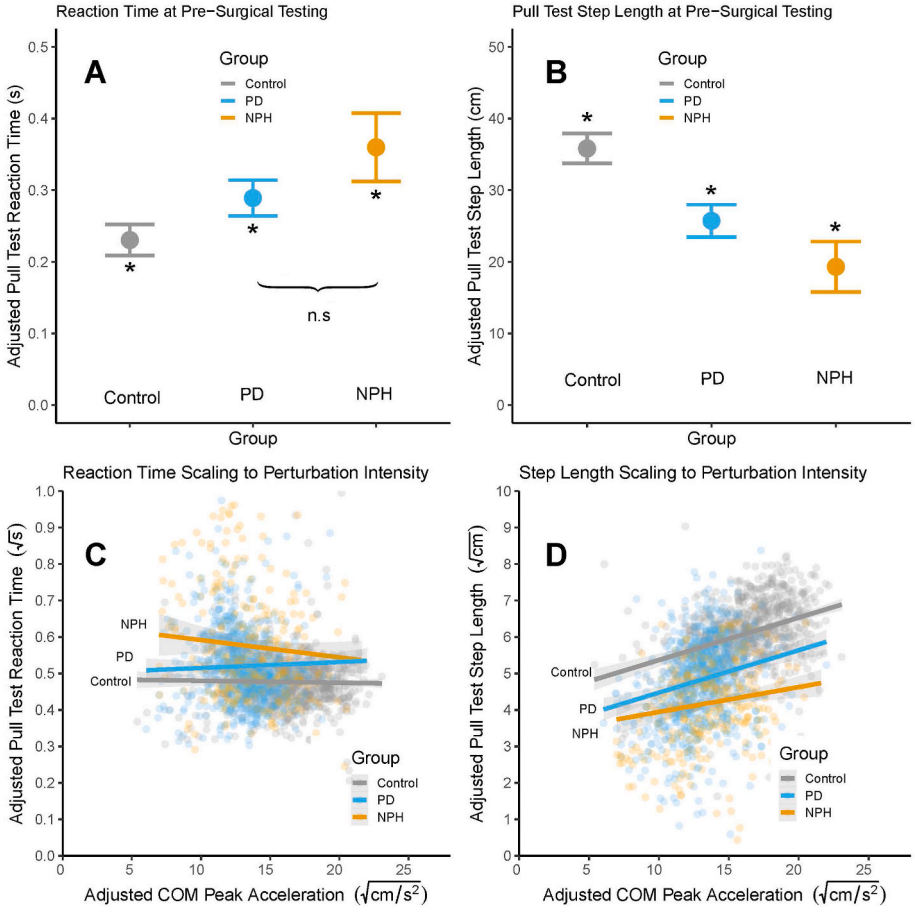

Fig. 2. Reactive postural response scaling of age-matched control subjects, PD patients, and NPH patients. **A**. Mean pull test reaction time at baseline grouped by patient population. **B**. Mean pull test step length at baseline grouped by patient population. **C**. Scaled reaction time as a function of pull test intensity grouped by patient population. **D**. Initial scaled step length as a function of pull intensity grouped by patient population.

controls scored as "2" or "3" and so comparisons to controls were not possible for these groups.

When separated by $UPDRS_{PT}$ score, control participants rated as "0" and "1" had faster reaction times than PD patients (Fig. 3A, $p = 0.02$ for "0", $p = 0.03$ for "1"), but not NPH patients (Fig. 3A, $p > 0.05$ for "0", $p > 0.05$ for "1"). There were no differences in mean reaction time between NPH and PD patients within any of the $UPDRS_{PT}$ score groups. When looking at the trend lines over the full range of adjusted pull intensities, no consistent patterns emerged with NPH patients scored as "1" and "3" appearing to demonstrate an inverse relationship to pull intensity where they appeared to react more slowly to harder pulls (Fig. 3B). However, the only significant differences in slope were between NPH and PD scored "3" (slope; $p = 0.002$) and between Control and PD scored "1" (slope; $p = 0.004$). PD patients scored as "0" did react slightly slower for a given pull as compared to healthy controls, but neither slope nor intercept were significant ($p = 0.02$, y-intercept $p = 0.053$, slope $p = 0.689$; PD vs. control). PD patients scored as "1" did react slightly slower for a given pull as compared to healthy controls, slope was significantly different, but not intercept ($p = 0.02$, y-intercept $p > 0.999$, slope $p > 0.004$; PD vs. control).

In terms of step length, control participants rated as "0" took larger steps than NPH participants rated as "0" ($p < 0.001$), but all other apparent differences between groups (Fig. 4A) were not statistically significant after adjusting for pull intensity. Because this indicated that much of the apparent differences in step length between groups within $UPDRS_{PT}$ scores were due to pull intensity, we finally looked at participants' ability to scale step length to increases in pull intensity (Fig. 4B). There were no statistically significant differences in either step scaling (slope) or the size of a step for a given pull intensity (y-intercept) within $UPDRS_{PT}$ scores between groups.

4. Discussion

The aim of this study was to compare the kinematics of postural instability in PD and NPH patients at their baseline surgical evaluations in order to look for distinguishing disease-specific features. While resting tremor, upper extremity and lateralized symptoms frequently distinguish PD from NPH patients, these symptoms are not always present in patients with PD.[14] As a result, patients coming for neurosurgical consultation regarding NPH frequently have unclear diagnoses or a "dual" diagnosis of parkinsonism or PD.[2] Given the primacy of gait and balance symptoms in NPH, a more quantitative method of assessment theoretically carries the benefit of being able to distinguish between the two diseases. In addition, postural instability in NPH improves with surgical treatment via VPS[13] while there are essentially no effective treatments for postural instability in PD. Previous work has demonstrated that the use of quantitative kinematics is helpful in examining gait and postural instability before and after surgery for patients with NPH and should be further investigated for patients with PD. While these patient groups undergo different surgical intervention (VPS for NPH and DBS for PD), the overall goal of surgical intervention improving postural instability remains the same and an important next step to investigate.[13] Quantitative methods allow for the possibility of detailing small changes in the postural response when assessing new treatments or understanding the pathophysiology of postural instability. Canonically, ordinal rating scales have been used in the clinical assessment of these patients, but with the limitations of between- and within-provider variability and subjectivity.

Here, we demonstrate that kinematically, the reactive postural response of NPH and PD patients appears very similar when grouped by similar disease severity (as defined by $UPDRS_{PT}$). Overall, differences seen between groups of patients mainly represent differences in the severity of their initial presentation. The relationship between step length and pull intensity (slope) for PD and NPH patients were almost identical regardless of $UPDRS_{PT}$ score, indicating that step length kinematics appears unlikely to be able to distinguish between patient groups at baseline evaluation assuming similar disease severity. Differences in step length between groups appeared to be solely in magnitude (y-intercept) which, again, was related to how severely affected their postural response was by the disease process. Interestingly, group differences in reaction time were not solely in magnitude as NPH participants had a steeper slope than control participants, but most of this difference appeared to be driven by participants scored as "2" and therefore were also likely driven by disease severity.

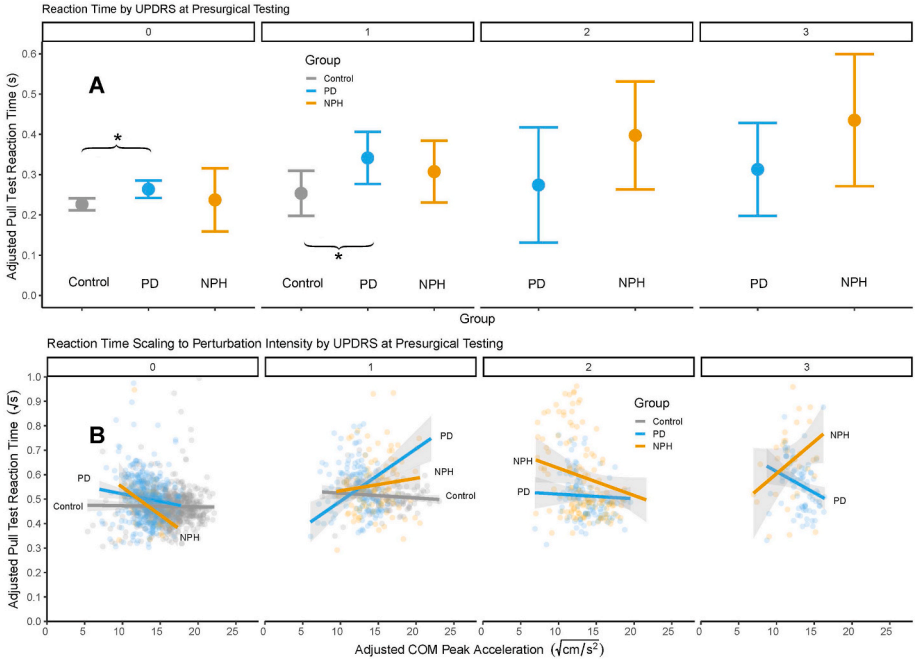

Fig. 3. Reactive postural response scaling of age-matched control subjects, PD patients, and NPH patients grouped by $UPDRS_{PT}$ score. **A**. Mean reaction time as a function of pull test intensity. **B**. Scaled reaction time as a function of pull test intensity.

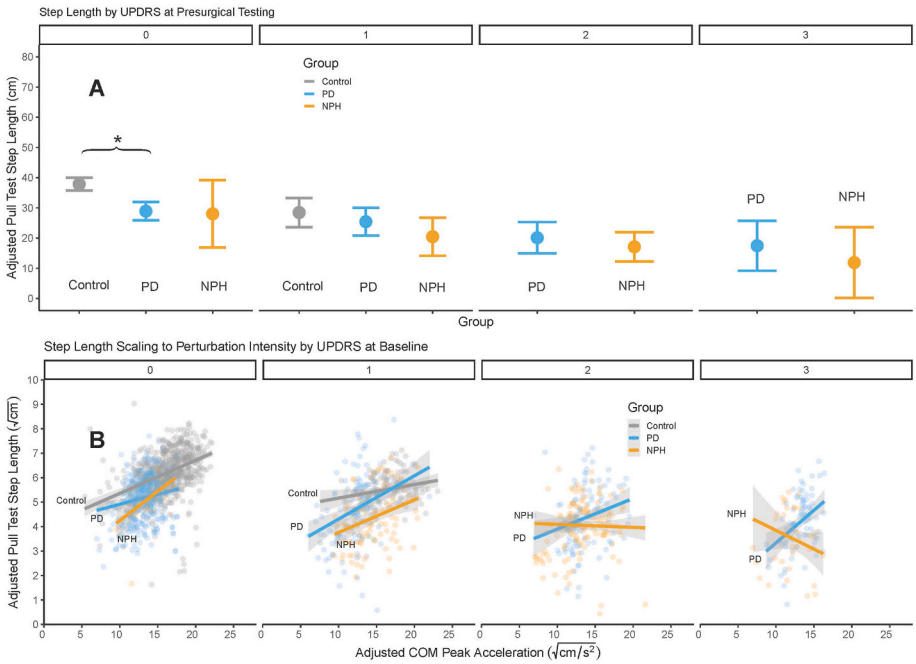

Fig. 4. Initial step length of age-matched control subjects, PD patients, and NPH patients grouped by $UPDRS_{PT}$ score. **A**. Mean initial step length as a function of pull test intensity. **B**. Initial scaled step length as a function of pull intensity.

4.1. Kinematic differences between NPH and control participants

When examining the kinematic profile of patients with NPH at baseline presentation compared to age-matched, healthy control participants, there were three notable findings. First, patients with NPH demonstrated a dramatically lower peak V_{COM} value and peak reaction foot velocity compared to healthy controls (Fig. 1). During any given pull test, a patient's V_{COM} follows a sinusoidal curve wherein it starts at zero, rises to a peak value as they are pulled backward and take a step, and drops back to zero as they recover. In order to recover from a perturbation, control participants typically take a large, fast step to slow their body down and recover. This results in one large peak V_{COM} and reaction foot velocity value. Patients who take smaller steps will typically demonstrate lower peak V_{COM} and reaction foot velocity values which more slowly return back to zero as they take many small steps to recover. Because V_{COM} and reaction foot velocity are partially determined by pull intensity, our statistical analysis controlled for pull intensity (as measured peak A_{COM} prior to taking a step) as control participants are typically pulled harder than patients. Even after adjusting for pull intensity, NPH patients had significantly smaller peak V_{COM} and reaction foot velocity values. This is likely due to the smaller initial step that NPH patients took to a given backwards perturbation (Fig. 2A and B).

Second, when examining our findings as a function of the step length response to a perturbation's intensity, we found that NPH patients react significantly slower and take significantly smaller steps compared to healthy controls when looking simply at the mean values of all trials. We purposefully varied the pull backwards, however, as the scaled response is important to examine since patient and control participants' postural response changes depending on pull intensity (Fig. 2C and D). Interestingly, at a group level, NPH and control participants' step responses differed in both step length and reaction time. In terms of step length, NPH participants' postural response was smaller in magnitude with almost identical scaled responses. This indicated that at a group level, kinematically, their ability to scale their initial step appropriately to a perturbation was similar to controls, but that their overall step length was smaller. When examining this difference within $UPDRS_{PT}$ scores, however, this disappeared, indicating that the group level differences may not represent a different kinematic strategy to responding to the pull, but rather is simply a consequence of disease severity.

Finally, in terms of reaction time, control participants demonstrated very little change in response to increasing pull intensity, possibly as a result of a floor effect. Even for easy pulls, their reaction time was ~0.200–0.250s and therefore, there may have been little room for improvement. This differs from a prior study in an older group of healthy control participants which was performed identically and showed that healthy controls maintained a scaled response with slower reaction times for easier pulls.[9] Thus, this may represent part of the aging process as individuals are able to react more quickly for intense perturbations, but not for less intense ones. NPH participants showed steeper slope and *y*-intercept values compared to controls on a group level, indicating that they scaled their reaction time for increasingly difficult pulls, but also reacted more slowly for a given pull. When examining these values within $UPDRS_{PT}$ scores, these differences disappeared and there was no clear pattern within $UPDRS_{PT}$ scores with most of the slow reaction times driven by patients in the "2" and "3" groups. This may indicate that, again, most of the difference on a group level is driven by the more severely affected participants.

4.2. Kinematics of the postural response cannot distinguish between NPH and PD

Overall, differences between NPH and PD participants were remarkably similar to those described above between NPH participants and controls. Participants with NPH demonstrated significantly slower V_{COM} and slower reaction foot velocity compared to patients with PD (Fig. 1). This is likely due to the differences in step length which were essentially differences of magnitude only as the slope of the scaled reaction time and step length responses were similar between groups. When examining kinematics separated by $UPDRS_{PT}$ score, there were no clear trends that could differentiate between NPH and PD patients either in the magnitude or the scale of the reaction time or step length responses. Only PD rated as "0" had significantly smaller steps than their normally rated control participant counterparts, however. This may indicate that the threshold for rating a movement disorder patient as "normal" is a bit lower than that of a control participant.

4.3. Limitations

There are a few limitations in our study. First, it is possible that sample size limited our ability to distinguish between patient groups, particularly since disease severity forced us to separate patients by $UPDRS_{PT}$ score. Larger datasets should be used to determine whether NPH and PD patients truly cannot be distinguished kinematically. For example, the step length response for PD and NPH participants rated as "0" appeared to be smaller in magnitude than healthy controls, but this was not statistically significant. More trials in more patients may be able to distinguish small differences in the postural responses of movement disorder patients rated as "normal" compared to healthy controls. The overlap between healthy controls and NPH participants, in particular, was less than desirable as NPH participants tend to be more severely affected. We would note, however, that each patient underwent 10–15 pull test trials at their evaluation and so each group contained hundreds of data points for comparison. A related limitation is the subjectivity of the $UPDRS_{PT}$ rating as small differences between controls and movement disorder patients rated as "0" may just be due to differences in subjectively rating a patient as having a "normal" response.

Given the results of this study, we would suggest that this limitation be turned around and used to better understand the underlying pathophysiology of effective treatment of postural instability for movement disorder patients. We are currently in the process of demonstrating that postural instability in NPH patients improves with VPS which can be demonstrated using kinematics.[13] However, there are no known effective treatments for postural instability in PD including dopaminergic medication and DBS[14] although LSVT-BIG therapy may improve certain aspects of postural instability.[15,16] This provides an ideal comparison between two patient groups with essentially kinematically identical postural responses as seen in this study, but differing treatment responses. Future research should therefore examine the cortical or subcortical dynamics of postural instability between these two groups using EEG, MEG, fMRI or other techniques, ideally combined with this kinematic assessment.

5. Conclusions

To our knowledge, there are no previous studies that examine differences in postural instability with quantitative kinematic assessment as an objective tool to distinguish between patients with NPH and PD. Using quantitative kinematic analysis, significant decreases exist in overall V_{COM}, scaled reaction time, and scaled step length for NPH patients as opposed to their PD counterparts. This is mainly due to the severity of presentation as NPH patients as a group were more likely to present with worse balance. When we examined these differences grouped by the current gold standard evaluation for postural instability, namely the $UPDRS_{PT}$ score, there were no reliable objective difference between NPH and PD patients. This may actually be an advantage for future studies aimed at examining the underlying mechanisms of postural instability since NPH patients improve with treatment whereas PD patients do not. Given the insights into the initial presentation, management and monitoring treatment response of postural instability in movement disorder patients, we would advocate for further incorporating objective kinematic data collection into their clinical visits.

Ethical standards statement

All human studies have been approved by the appropriate ethics committee and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

Funding

This study was funded by MnDRIVE, a collaboration between the state of Minnesota and the University of Minnesota.

CRediT authorship contribution statement

Jacob T. Hanson: Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing. **Luke T. Sabal:** Methodology, Resources, Writing – original draft. **James N. Jean:** Formal analysis, Methodology, Validation, Writing – original draft. **Alec Jonason:** Methodology, Resources, Writing – original draft. **Reid Johnson:** Writing – original draft. **Thomas Lisko:** Formal analysis, Methodology, Writing – original draft. **Yeng Moua:** Writing – original draft. **Robert A. McGovern:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wnsx.2024.100299.

References

1. Marras C, Beck JC, Bower JH, et al. On behalf of the Parkinson's foundation P4 group. Prevalence of Parkinson's disease across north America. *Npj Parkinson's Disease*. 2018;4(1):1–7. https://www.nature.com/articles/s41531-018-0058-0.
2. Mostile G, Fasano A, Zappia M. Parkinsonism in idiopathic normal pressure hydrocephalus: is it time for defining a clinical tetrad? *Neurol Sci*. 2022;43(9):5201–5205. https://doi.org/10.1007/s10072-022-06119-3.
3. Goetz CG, Tilley BC, Shaftman SR, et al. Movement disorder society-sponsored revision of the unified Parkinson's disease rating scale (MDS-UPDRS): scale presentation and clinimetric testing results. *Mov Disord*. 2008;23(15):2129–2170. https://doi.org/10.1002/mds.22340.
4. Burns ER, Stevens JA, Lee R. The direct costs of fatal and nonfatal falls among older adults—United States. *J Saf Res*. 2016;58:99–103. https://doi.org/10.1016/j.jsr.2016.05.001.
5. Pujari S, Kharkar S, Metellus P, et al. Normal pressure hydrocephalus: long-term outcome after shunt surgery. *J Neurol Neurosurg Psychiatry*. 2008;79(11):1282–1286. https://doi.org/10.1136/jnnp.2007.123620.
6. Grasso G, Torregrossa F, Leone L, et al. Long-Term efficacy of shunt therapy in idiopathic normal pressure hydrocephalus. *World Neurosurg*. 2019;129:e458–e463. https://doi.org/10.1016/j.wneu.2019.05.183.
7. Leddy AL, Crowner BE, Earhart GM. Utility of the Mini-BESTest, BESTest, and BESTest sections for balance assessments in individuals with Parkinson disease. *J Neurol Phys Ther*. 2011;35(2):90–97.
8. Winser SJ, Kannan P, Bello UM, et al. Measures of balance and falls risk prediction in people with Parkinson's disease: a systematic review of psychometric properties. *Clin Rehabil*. 2019;33(12):1949–1962. https://doi.org/10.1177/0269215519877498.
9. Daly S, Hanson JT, Mavanji V, et al. Using kinematics to re-define the pull test as a quantitative biomarker of the postural response in normal pressure hydrocephalus patients. *Exp Brain Res*. 2022;240(3):791–802. https://doi.org/10.1007/s00221-021-06292-5.
10. Relkin N, Marmarou A, Klinge P, Bergsneider M, Black PM. Diagnosing idiopathic normal-pressure hydrocephalus. *Neurosurgery*. 2005;57(3 Suppl):S4–S16. https://doi.org/10.1227/01.neu.0000168185.29659.c5. ; discussion ii-v.
11. Postuma RB, Berg D, Stern M, et al. MDS clinical diagnostic criteria for Parkinson's disease. *Mov Disord*. 2015;30(12):1591–1599. https://doi.org/10.1002/mds.26424.
12. Schepers M, Giuberti M, Bellusci G. Xsens MVN: consistent tracking of human motion using inertial sensing. *Xsens Technologies*; 2018:1–8. https://www.researchgate.net/publication/32400 7368_Xsens_MVN_Consistent_Tracking_of_Human_Motion_ Using_Inertial_Sensing/link/5ab8be2f0f7e9b68ef51f7ba/download.
13. Wacek A, Jean J, Jonason A, et al. Longitudinal improvement in postural instability is distinct from gait in treated adult hydrocephalus. *medRxiv*. 2022. https://doi.org/10.1101/2022.12.05.22282985.
14. Palakurthi B, Burugupally SP. Postural instability in Parkinson's disease: a review. *Brain Sci*. 2019;9(9):239. https://doi.org/10.3390/brainsci9090239.
15. Godi M, Arcolin I, Giardini M, Corna S, Schieppati M. Responsiveness and minimal clinically important difference of the Mini-BESTest in patients with Parkinson's disease. *Gait Posture*. 2020;80:14–19. https://doi.org/10.1016/j.gaitpost.2020.05.004.
16. Iwai M, Koyama S, Takeda K, et al. Effect of LSVT® BIG on standing balance in a Parkinson's patient: a case report. *Physiother Res Int*. 2021;26(4), e1921. https://doi.org/10.1002/pri.1921.