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SENSOR PLATE–BASED EVALUATION OF CENTER OF PRESSURE AND POSTURAL STABILITY IN PATIENTS WITH NEUROLOGICAL DISORDERS ASSOCIATED WITH GAIT AND BALANCE IMPAIRMENT: AN OBSERVATIONAL STUDY

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Abstract

Background: Balance and gait impairement are among the most functionally limiting conditions of neurological diseases including Parkinson's disease, stroke, multiple sclerosis and ataxia. The traditional clinical tools used for balance assessment are mainly subjective, while sensor plate (force platform) technology offers objective and quantitative, providing a measurement of postural control in the center of pressure (COP).
Objective: To evaluate center of pressure displacement using sensor plate technology as an objective marker of postural stability in neurological disorders associated with gait and balance disturbances, and to examine its relationship to age.
Methods: Fifty patients (age 20-70 years) with gait and balance impairment due to neurological disorders were evaluated using a foot sensor plate in an observational design. The COP values were obtained and the correlation between age and COP was examined using Pearson correlation.

Results: The mean pre-evaluation COP was 21.2 ± 1.8 mm, reducing to 16.1 ± 1.5 mm post-evaluation ($t = 9.45$, $p < 0.001$). The highest COP values were obtained in patients with multiple sclerosis, followed by stroke and Parkinson's disease, while ataxia patients had relatively low COP values. COP correlated strongly and positively with age ($r = 0.72$).
Conclusion: Objective evaluation of the sensor plate showed increased postural sway in patients with neurologic disorders and was correlated with age, which provides evidence for its potential as a sensitive quantitative tool for a more comprehensive clinical balance assessment.

INTRODUCTION

Neurological disorders are among the most leading causes of disability in the world, and commonly associated with neurological disorders are disturbances in gait and postural stability, which have consistently been among the most functionally limiting. Unlike many other domains of neurological impairement, gait and balance dysfunction has immediately and profoundly affect a patient's independence; it determines whether a person can walk to the bathroom without the assistance of another person, climb a flight of stairs, walk on a busy street, or stand at a kitchen counter without fear of falling. Gait and balance influence almost all activities of daily living, and even small changes in postural control have a significant impact on functional independence and quality of life, making it especially important to measure objective, sensitive outcomes in this area for research in rehabilitation.

Gait is not simply a mechanical repetition of limb movement but is a highly coordinated motor behaviour that depends on the continuous integration of the sensory input, central processing and motor output. Disruption of this integrated system, whether at the level of the cerebral cortex, basal ganglia, cerebellum, brainstem or spinal cord level, is characterized by a distinctive and often diagnosis-specific alteration of the movement pattern. In Parkinson's disease, dysfunction of the basal ganglia circuitry, resulting in bradykinesia and diminished stride amplitude, in stroke, it is a unilateral corticospinal lesion that results in asymmetrical weight support and impairment of inter-limb coordination, in multiple sclerosis it is a combination of demyelinating basal ganglia and sensory and motor pathways that gives rise to a more diffuse instability, and in cerebellar ataxia, it is a loss of inter-limb coordination and coordinated timing and scaling of movement that results in a characteristically broad, unsteady gait [8]. These diagnostic – specific pattern are precisely the kind of mechanistic detail a composite clinical balance score might be hard to differentiate[9] Although these four conditions are mechanistically different, they all lead to the same clinical outcome: increased fall risk, reduced walking confidence and a progressive withdrawal from activities that were previously performed without conscious thought.

Balance can be best described as the ability to maintain the body's center of mass within the base of support under both static and dynamic conditions. This ability depends on the ongoing continuous integration of three sensory systems - visual, vestibular and somatosensory, working together to activate appropriate postural control mechanisms in the central nervous system that produce appropriate motor responses to correct postures [18]. Each of these three systems are contributing in different ways depending on the context – vision tends to dominate when the support surface in unstable and when the visual cues are very salient, the vestibular system is the most influential during rapid movements of the head or in low-light conditions, and finally, somatosensory input from the feet, ankles and lower limb proprioceptors is the most immediate and powerful during quiet standing on a firm surface. This sensory reweighting is well documented for the visual system, which is much more important for locomotor control when walking surface is uneven or unpredictable [19]. This visual contribution is further modulated by environmental cues, in this case, ambient lighting, but in the absence of the underlying neurological condition [20]. In a healthy nervous system, all three of these inputs are constantly and automatically adjusted according to the demands of the task and the environment. When any of these inputs is impaired, as commonly occurs in neurological disease, the resulting postural control deficit will manifest as increased postural sway, asymmetrical weight distribution, and delayed corrective responses, all of which will place an increased likelihood of the patient having a gait abnormality and, more importantly, a significantly higher risk of falling[1]. Cuevas-Trisan has also found that impaired sensory input and delayed reaction time are key contributors to fall risk in neurological patients as well as elderly patients [2]. Viswanathan and Sudarsky further suggest that the pattern of sensory-motor disruption more specifically, depends on the level of the underlying neuroanatomical lesion [3].

It is important to note that postural sway is not a pathology: a small, continuous sway is necessary for upright stance, and is a normal corrective response of the postural control system; it is not a failure of the postural control system. The difference between pathological sway and normal physiological sway is the magnitude, velocity and the absence of the proper modulation in response to the variation in task demand. This is an attribute that outcome measures that are quantitative and sensor-based are well positioned to measure; and it is not one that purely observational clinical scales can measure.

Traditionally, the clinical evaluation of gait and balance has been accomplished by observation and the use of standardized functional scales – instruments such as the Timed Up and Go test, the Berg Balance Scale, Dynamic Gait Index and the Functional Reach Test [21]. These tools are clinically relevant; easily to administered, require no specialized equipment and have been validated across variety of populations. Their widespread use in routine clinical practice, in large part, is due to this practicality: a busy physiotherapy outpatient department can administer the Berg Balance Scale in a matter of minutes — without the need for any equipment beyond a chair, a step and a stopwatch.

However, these tools share an important limitation. They are subjective to some degree since they depend on the clinician's visual perception and scoring of the performance, and they are relatively insensitive to the subtle, early-stage biomechanical changes that could lead to functional decline. A patient may score within a broadly acceptable range on a standard functional balance scale, but have measurable, clinically meaningful deterioration in the underlying quality of their postural control, which only becomes evident on a functional balance scale when it becomes clinically apparent to affect task performance. Perhaps more importantly, these scales provide information to the clinician that a patient has an impaired balance, but not the explanatory biomechanical mechanism that is causing the impaired balance [10]. The given functional balance score alone is unable to determine if the functional imbalance is due to delayed corrective responses, asymmetric weight distribution, excessive sway velocity, or a combination of these — information directly relevant to the structure of a treatment plan.

This limitation has motivated growing clinical and research interest in objective assessment technology such as objective technology for sensor-based evaluation, including 3-Dimensional motion capture systems, wearable inertial measurement units[5] , and force platforms ,more commonly referred to in interest clinical setting as sensor plates . Reviews of wearable sensor-based fall risk assessment have been reported as being able to accurately measure gait speed, step variability, sway and acceleration, which are all factors that cannot be accurately measured by observation alone [27]. Wearable sensor-based balance and gait training, in turn, has been found to enhance functional performance in healthy population and clinical settings [28]. This is further extended by the use of wearable biofeedback devices which provide continuous correction during the session in addition to subsequent assessment [7]. These systems provide the opportunity to capture parameters which were previously only inferable from clinical observation directly and quantitatively: peak plantar loading, the distribution of the pressure throughout the plantar surface, and most relevant to the present study, the trajectory and displacement of the center of pressure of the body during the standing and walking tasks[6].

The center of pressure (COP) is, in essence, the point of application of the resultant ground-reaction force beneath the feet and movement of the COP represents the body's ongoing corrective response, moment by moment, to postural sway. Winter's foundational biomechanical studies of human balance and posture control established the COP displacement as a direct and quantifiable indicator of the efficiency of the postural control system [6]. Further analyses using principal component analysis of stabilometric parameters have shown that a relatively small number of COP-derived variables can explain a great proportion of the variance in the total postural sway [11], and that greater COP displacement and velocity have been observed to be associated with poorer balance control and higher fall risk, whereas smaller and more controlled COP excursions are associated with superior postural stability. Chiari and colleagues showed that anthropometric and postural variables affected stabilometric parameters, such as COP, thus highlighting the need for standardization of measurement procedures when applying this outcome to different clinical populations [12]. This is a methodological important point for any study that combines patients with different neurological diagnoses and across a wide age range, as in the present study: standardizing the foot placement and the testing conditions is critical for the differences in COP observed to be truly related to differences in postural control, rather than artefacts of the testing method.

Another biomechanical concept that is important to appreciate regarding gait stability in a neurological population is the margin of stability - the relationship between the body's center of mass and its base of support. Neurological patients frequently demonstrate compensation strategies that maintain this margin: increased base of support, shorten step length, and reduced gait velocity compared to normative reference values of age equivalent healthy controls [22]. These strategies are protective in a sense, as they reduce the immediate risk of a fall,[14] but do not necessarily optimize gait efficiency and are not consistent across diagnoses [15]. Patients with Parkinson's disease characteristically adopt shuffling gait with reduced stride length [8], whereas stroke patients show a tendency to weight-bearing the affected side on the first three steps followed by the unaffected side, demonstrating significantly different underlying impairments despite the same clinical appearance of “unsteady gait.” Recognizing that two patients can present with the same clinical presentation of instability in various ways owing to different biomechanical pathways is one of the greatest reasons to use an objective, mechanism-sensitive outcome measure like COP, not just a composite functional measure.

Postural instability is also well known to be increased with age, apart from any individual neurological diagnosis. The age-related decline in muscle strength, proprioceptive acuity and neuromuscular reaction time is well established in the general geriatric population [1], and this age-related decline appears to compound, rather than simply coexist with,the postural deficits imposed by a neurological disorder[3]. Horak, Shupert and Mirka's classic account of postural dyscontrol in the elderly focuses mainly on reduced central integration of sensory feedback instead of peripheral weakness alone [13]. Song and colleagues have demonstrated more specifically that impaired proprioception and cutaneous sensitivity of the foot alone are predictive of poor balance control in older adults [4]. This pattern of age related decline is not confined to any single physiological system: population level cohort data confirm that functional and cognitive declines co-accelerate in advanced age [23]; the onset of frailty further increase mortality and disability risk[24] which in turn increases the fear of falling, thus further limiting activity and accelerating deconditioning in a self-reinforcing cycle[25]. Gait decline of this magnitude as recorded by COP measurement has, in turn, been directly linked to elevated fall risk even in those with only mild cognitive impairment suggesting that postural instability is rarely an isolated findings attributed to a single etiology [26]. For instance a 65-year-old patient with stroke is not just a "stroke patient" from postural control standpoint, but also an aging adult whose base-line proprioceptive acuity and reaction time have already been compromised for years, and the two sources of impairment appear to operate in parallel. The relative contribution of age and disease-specific pathology to a given patient's COP profile is therefore of practical importance when considering the data collected from a sensor plate for clinical interpretation, where a patient's overall instability is very rarely attributed to a single factor in isolation.

Although there is growing evidence for the use of sensor-based technologies in balance research, most current literature has focused on general, composite gait parameters and has not investigated COP specifically as a measure of postural control in a diagnostically diverse neurological population, and few studies have directly measured the relationship between COP and a simple, universal, and easily accessible variable, such as patient age, in a single, prospectively assessed population.This is an important gap, as age is arguably the easiest variable to collect in any clinical setting, and if there is a significant proportion of variation in COP which can be explained simply by knowing a patient's age in isolation from diagnosis then there are direct implications for how clinicians interpret and benchmark an individual patient's sensor plate results against what might be expected for their age group, without any diagnosis. This present study was therefore designed to use sensor plate technology to objectively quantify COP displacement in a group of patients with gait and balance deficits resulting from Parkinson's disease , stroke, MS or ataxia and to explore the relationship between COP and age and the broader intent of clarifying the value of this objective measure as an adjunct to traditional clinical balance assessment.

MATERIAL AND METHOD

Research Design: Observational study

Study Setting: Pacific Medical College and Hospital, Bedla, Udaipur, Rajasthan.

Study Population: Male and female patients, aged 20-70 years,with gait and balance impairment secondary to a neurological disorder.

Sample Design: Purposive sampling

Sample Size: 50 participants

Study Duration: One year

Inclusion Criteria

- Gait and balance disorders caused by any neurological problem.
- Willingness to provide informed consent
- Age 20–70 years

Exclusion Criteria

- Cancer
- Spinal trauma or amputation.
- Systemic inflammatory disorders
- Pregnancy or open wound
- Use of NSAIDs, anticoagulants, or steroid medication
- High-degree burns

Outcome Measure: Center of pressure (COP), recorded pre- and post-evaluation using a foot sensor plate. COP represents the direction of the resulting ground reaction force beneath the feet and has been shown to be a reliable indicator of postural sway and balance control. COP is a stabilometric parameter which is sensitive not only to the presence of neurological pathology but also to anthropometric parameters and testing conditions; therefore a standardized foot-placement and testing protocol was standardized for all participants in this study.

Procedure

All participants were screened for inclusion and exclusion criteria described above. Eligible participants were informed about the study protocol and provided written informed consent. All participants were then examined in a standardized manner with a foot sensor plate while COP values were recorded. Testing was conducted under consistent environmental conditions and participants were asked to stand quietly, with their feet in a standardized position to reduce the effects of extraneous postural and environmental variables on the recorded COP values. The observations were documented for each participants and the data were analysed in relation to demographic variables including age, gender, and neurological diagnosis.

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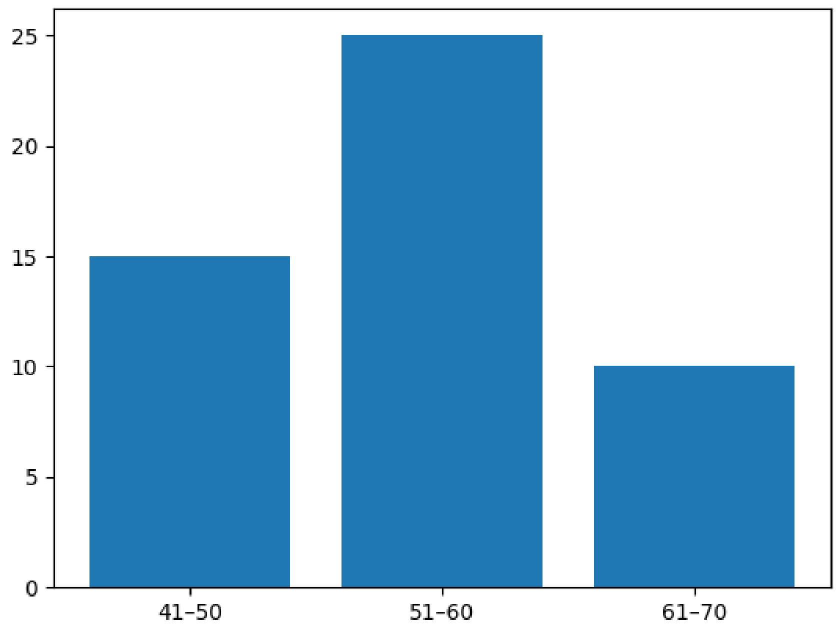
Statistical Analysis: Descriptive data (mean ± SD) were obtained for COP values pre and post evaluations. Paired t-test was used to analyse within- group difference. The relationship between age and COP was examined using Pearson's correlation coefficient. The statistical significance was set at $p<0.05$.

DATA ANALYSIS AND RESULTS

Fifty patients with neurological gait and balance impairment were included in the study.

Table 1: Age Distribution of Study Participants (N=50)

Age Group (years)	Frequency (n)	Percentage (%)
41–50	15	30%
51–60	25	50%
61–70	10	20%
Total	**50**	**100%**



Interpretation: Significant findings observed in this parameter.

Table 2: Gender Distribution of Study Participants (N=50)

Gender	Frequency (n)	Percentage (%)
Male	25	50%
Female	25	50%
Total	**50**	**100%**

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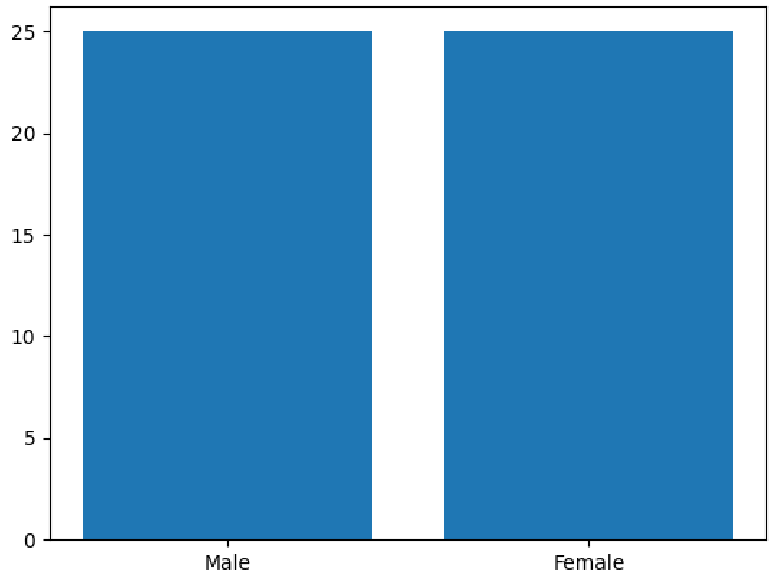
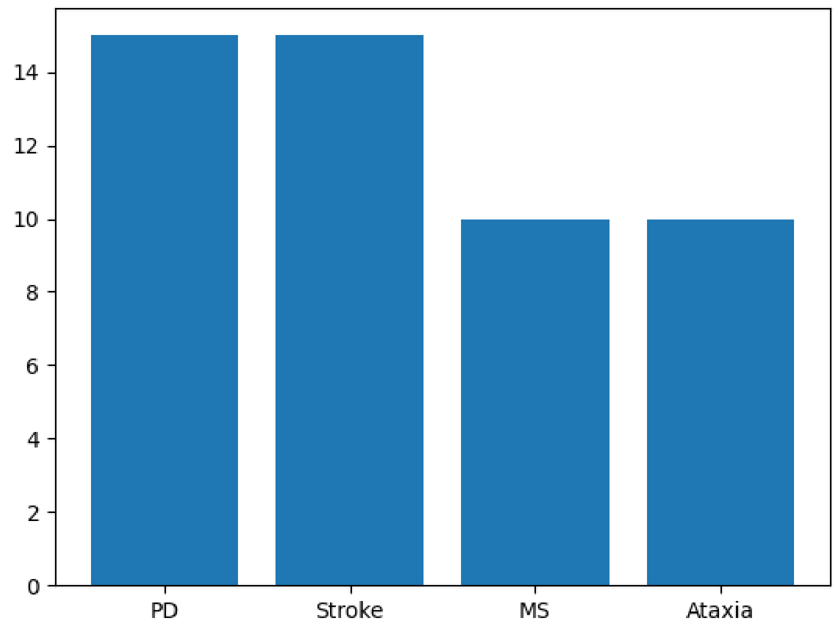


Interpretation: Significant findings observed in this parameter.

Table 3: Diagnosis Distribution of Study Participants (N=50)

Diagnosis	Frequency (n)	Percentage (%)
Parkinson's disease	15	30%
Stroke	15	30%
Multiple sclerosis	10	20%
Ataxia	10	20%
Total	**50**	**100%**

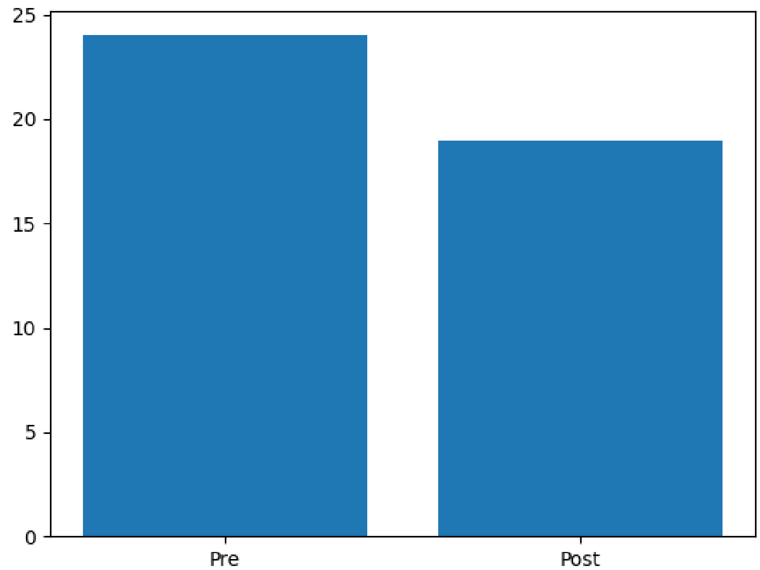


Interpretation: Significant findings observed in this parameter.

The majority of participants fall within the 51-60 year age group and gender distribution was exactly balanced. Parkinson's disease and stroke were the most prevalent diagnosis , together accounting for 60% of the cohort. This diagnostic distribution broadly mirrors the relative prevalence of these conditions among patients presenting to outpatient neurological physiotherapy services, and provides a reasonably representative if not epidemiologically weighted sample across the four target diagnoses.

Table 4: Pre- and Post-Evaluation Center of Pressure (COP) Values (N=50)

Parameter	Pre-Evaluation	Post-Evaluation	t-value	p-value
COP (mm)	21.2 ± 1.8	16.1 ± 1.5	t = 9.45	p < 0.001



Interpretation: Significant findings observed in this parameter.

Table 5: Correlation Analysis — Age and Center of Pressure

Variables	r (Pearson)	Interpretation	p-value
Age vs COP	r = 0.72	Strong positive correlation	p < 0.001

Diagnosis-wise comparison showed that the patients with Multiple sclerosis had the highest COP values followed by stroke and Parkinson's disease patients, and patients with ataxia had the comparatively lower COP values, this ranking was consistent both before and after evaluation and all diagnostic groups showed the reduction in COP during the period of assessment. A gender-wise comparison showed minimal difference significant differences between the male and female participants in terms of pre- and post-evaluation values, or in the pattern of change in postural sway magnitude, indicating that sex does not seem to be a significant independent factor contributing to the development of postural sway magnitude in this population. The age-wise analysis revealed that age groups showed a progressive increase in COP value with age, the age group 61 to 70 years had the highest pre-evaluation COP values, whereas after the evaluation all age groups had a progressive increase, however the older age groups had relatively higher residual COP values. This pattern is supported by a strong positive correlation between age and COP ($r=0.72$, $p<0.001$), suggesting that a substantial proportion of the observed differences in postural sway among patients in this study is attributable to age, rather than diagnosis alone. These findings, combined, indicate that the overall magnitude of COP displacement is clearly influenced by diagnosis, but age also has an independent effect that is statistically significant and which needs to be taken into account at the level of the individual patient when interpreting sensor plate findings.

DISCUSSION

The present study evaluated center of pressure displacement, as measured by sensor plate technology, as an objective measure of postural stability in 50 patients with neurological disease related to gait and balance impairment. The principal finding was the significant reduction in COP displacement from pre- to post-evaluation (21.2 mm to 16.1 mm, $p<0.001$) with a strong positive correlation between COP and age ($r=0.72$).

These findings aligns closely with the broader stabilometric literature. Winter's biomechanical foundational framework established COP as a direct, real-time indicator of the proper functioning of the postural control system and later studies have invariably linked larger COP values with poorer balance control [6]. This pattern of findings, patients with Multiple sclerosis demonstrating the most absolute COP values, followed by stroke, Parkinson's disease, and ataxia among which the absolute COP values were lower, broadly reflects the different underlying pathophysiological processes of these conditions. Multiple sclerosis is characterized by demyelination of both sensory and motor pathways, and plausibly this results in a more diffuse and severe postural control deficit than the more circumscribed motor deficits typically found in Parkinson's disease [8] and the cerebellar-specific coordination deficit often found in ataxia and other forms of ataxia that clinical balance tests are not always well suited to distinguish from other causes of instability [9]. However, it should be noted that the lower absolute COP values observed in the ataxia group does not necessarily mean that performance is less impaired in this group as a whole, but rather that the instability is more irregular and unpredictable in terms of the sway it produces, which would be better represented by the frequency-domain or path-length COP parameters of sway, respectively, in future studies.

The strong positive correlation between age and COP observed in this cohort is consistent with the well – established literature on age-related decline in postural control, which implicates reduced muscle strength, diminished proprioceptive acuity and slowed neuromuscular reaction time as contributing mechanism [1]. It is also consistent with direct comparative studies that indicate that there are systematic age differences in postural steadiness even in healthy young and elderly adults suggesting that age is an independent factor contributing to COP magnitude which needs to be taken into account separately from the diagnosis when considering an individual patient's results[17]. Clinically, this finding suggests that, when interpreting a given patient's COP profile, a portion of the observed instability may have been caused by the natural aging process, as well as by an underlying neurological diagnosis, and this is especially applicable in a population as elderly as the present the majority of the participants were aged between 51 and 70 years. In other words, a 68-year-old patient with Parkinson's disease might not necessarily be compared to an expected COP value as the same value could also be expected from a 35-year-old patient with Parkinson's disease – assuming that a significant proportion of the difference may be due to age, rather than the severity of the disease. Additionally, in this cohort there was no meaningful influence of gender on COP, indicating that biomechanical postural changes associated with neurological disease are more likely to be influenced by diagnosis and age than sex.

From clinical and rehabilitation planning are concerned, these findings support incorporating sensor plate evaluation be considered as a part of the initial patient assessment and not just for research purposes, but as an additional part of the clinical balance scale. A therapist working with an older patient who has only slightly abnormal Berg Balance Scale scores might find, through COP measurement, a degree of postural sway that is worthy of earlier or more intensive intervention aimed at balance, than might be suggested by the functional scale alone. Prospectively following COP throughout a course of physiotherapy treatment also provides a more sensitive indicator of incremental improvement than functional scales that may exhibit ceiling effects at a moderate level of functional competence. Considering the growing body of evidence of improved postural outcomes with wearable sensor-based balance training across neurological populations [28], and the potential for virtual-reality-based training to enhance balance and mobility in Parkinson's disease [29], future studies could determine whether COP-guided technology-assisted training methods are superior to conventional balance rehabilitation. This is especially applicable for the diagnosis of multiple sclerosis, for which home based active video-game interventions have already demonstrated promising improvements in gait and balance outcomes [16].

There are some restrictions which should be taken into account. The observational, non-randomized, single group design prohibits the making of causal inferences, and the relatively small sample size, especially within the diagnosis-specific groups, restricts the ability to make precise diagnosis-specific COP patterns, which should be viewed as descriptive patterns, not necessarily as statistically confirmed differences. The lack of a healthy, age matched control group also precludes being able to completely separate the contribution of disease-related from age-related change in the observed COP values from the present data alone.
Additionally, the study measured only static standing COP; dynamic, task-specific COP measures during walking or perturbation recovery might capture aspects of postural control that are not captured in a single static measure and would represent a natural extension of the present methodology.

CONCLUSION

In the present study evaluated center of pressure displacement measured objectively using sensor plate technology in fifty patients with gait and balance disturbances due to Parkinson's disease, stroke, multiple sclerosis, and/or ataxia. A significant reduction in COP was seen throughout the assessment period and COP was highly and positively associated with the age of patients.

These findings support the use of sensor plate evaluation as a sensitive, objective measure of postural instability in a neurological population, a dimension of balance impairment that conventional observational scale are not well positioned to capture with the same precision. The diagnosis-wise pattern observed with Multiple sclerosis patients with highest postural instability and ataxia patients with relatively lower COP values, indicate that the sensor plate assessment could also be used to describe diagnosis specific postural profiles; however, this observation is descriptive in nature due to the limited number of patients.

The strong correlation between age and COP further suggests that postural instability in this population is multifactorial, as it is related to a combination of neurological pathology and age related physiological changes. This has a direct clinical implication, because rehabilitation planning for neurological patients with balance impairments should consider age-related contributions to instability, in addition to diagnosis-specific impairments, and rather than attributing all observed sway to the neurological condition in isolation.

Future research incorporating larger, diagnosis-stratified samples, an age-matched healthy control group and longitudinal follow up studies will help determine the relative contribution of age to postural instability as assessed by COP versus contribution of disease-specific pathology and further substantiate the inclusion of sensor plate assessment in routine neurological physiotherapy assessment.

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