A Brief Overview: The Utility of Wearable Motion Sensor Technology for Neurodegenerative Diseases.

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Abstract: - Neurodegenerative diseases are conditions that affect a patient's motor function capabilities, hindering human movement, limiting the ability to perform activities of daily living (ADLs) and negatively impacting patient quality of life (QoL). Currently, clinical assessments are subjective in nature, and quantitative assessment would be an excellent supplemental tool to provide clinicians with support in clinical decision making. Inertial measurement units (IMUs) are unique sensor-based technologies with potential applicability as clinical assessment technology in patients with neurodegenerative diseases. Moreover, gold-standard motion capture (MOCAP) technology is expensive and limited to research-specific use, making it unavailable to patients and, therefore, impractical for clinical use. IMU sensor-based technology can track human movement in real-time, are cost-effective, and provide data to the clinician as a quantitative output. Thus, it is the aim of this paper to discuss the potential use of IMU sensors as a clinically relevant tool.

Key-Words: - Neurodegenerative Disease, Wearable Motion Sensor, Human Movement, Inertial Measurement Unit, Motion Capture, Biomechanics.

Received: March 25, 2025. Revised: June 16, 2025. Accepted: July 13, 2025. Published: September 30, 2025.

1 Introduction

Impairment of motor function can result from a multitude of acute and chronic conditions that affect key structures of the central nervous system (CNS). Specifically, neurodegenerative diseases (NDs) like Alzheimer's disease (AD), Parkinson's disease (PD), Huntington's disease (HD), and amyotrophic lateral sclerosis (ALS) all progress towards a variable degree of physical and cognitive degradation based on unique pathologies all tracing back to neuronal loss [1, 2, 3, 4, 5]. Furthermore, neurological dysfunction occurring in ND patients results in such symptoms as muscular rigidity, weakness, or atrophy; commonly leading to motor pattern-specific functional limitations compromising the patient's ability to perform human movement [2, 3, 6].

Aging is a risk factor for the diagnosis of NDs [7]. Age-related decline can still occur in healthy elderly populations affecting both neuromuscular structures and, in turn, mechanical function [8]. However, in an ND patient population, this decline affecting motor control and physical function may be more severe, exacerbate functional limitations, due to disease-specific damage to neuronal structures of the CNS [7, 9]. Concurrently, the adverse effects on movement capabilities directly impact ND patient's ability to perform activities of daily living (ADLs) and thus, independence in everyday function [6].

Moreover, reductions in range of motion (ROM) are typically observed in ND patients experiencing symptoms of motor dysfunction, commonly in the form of gait impairment [9]. Gait impairment results in a multivariate increased fall risk, and thus, a direct increase in risk of injury and hospitalization [9, 10]. Therefore, quality of life (QoL) in ND patients can exponentially decline without timely identification, monitoring, and treatment of motor dysfunction symptoms.

Motion capture (MOCAP) systems collect biomechanics-related data on human movement. Human MOCAP data is traditionally collected in a movement research laboratory using research-grade visual-optical systems like the Optotrak Certus (OC3D) or advanced setups like the Vicon 20-camera systems [11]. However, these research-grade systems are expensive, require state-of-the-art arrangement of the devices and accompanying external visual-optical technologies, while necessitating a dedicated space to conduct movement-specific activities in direct visible line-of-sight of the visual-optical MOCAP system [12]. In fact, a full MOCAP system with multiple cameras can range up to $120,000 USD [11]. Thus, although visual-optical MOCAP systems are commonly considered the gold standard in biomechanics research, these technologies are not without limitations or barriers to use in the clinical setting.

Wearable motion sensors can revolutionize clinical care for ND patients by quantifying data and visualizing key performance metrics collected during clinical visits and assessments [12, 13, 14]. Although research on biomechanics of ND patients is a continued effort, there has not yet been an investigated technology adopted and implemented for dedicated use within the clinical setting for ND assessment [15]. Specifically, with patients experiencing movement dysfunction symptoms, inertial measurement units (IMUs) are wearable sensor-based devices that can collect, track, and classify data on human movement in real-time [16]. This means that wearable sensor-based devices may bear capability to depict and identify perturbations from tremors, postural sway, or other activities involving human movement. Moreover, at the time of writing for this paper and to the knowledge of the authors, there is no exact unified consensus on standardized technology used by clinicians to generate quantitative biomechanical data to support ND patient care and treatment [17]. Thus, IMUs are cost-effective and easily obtainable; making recent advancements in sensor-based technologies relevant for clinical consideration to quantify human movement. Therefore, it is the intent of this paper to discuss the utility of IMU sensor-based technology as a potential clinically affordable quantitative assessment tool for human movement analytics in ND patients.

1.1 Disease-Specific Considerations

Each ND bears a unique pathology, however, there are some similarities in functional limitations and disease-specific concerns.

1.1.1 Parkinson's Disease

NDs progressively degrade the physical and cognitive condition, as well as the motor function capacity, of the diagnosed patient population [1, 2, 18]. In PD, disease progression occurs due to gradual degradation of the dopaminergic neurons within the pars compacta region (SNpc) of the substantia nigra (SN), leading to motor deficits and dysfunction [19, 20]. Patients diagnosed with PD experience physical impairments characterized by the following key motor symptoms: 1) tremors while at rest, 2) muscle stiffness, 3) slowed movements or loss of motor control during movement, and 4) postural instability [18]. Furthermore, this disease annually impacts a significant portion of the elderly over 60 years of age, defining PD in part as an aging-related issue [21].

Although the current standard of care for PD patients is primarily through pharmacological intervention, there have been investigations covering multimodal approaches in PD patients involving supplemental exercise and physical activity finding improvements in functional movement capacity [22]. Thus, PD bears significant implications on the ability to perform human movement if intervention or diagnosis is not delivered in a timely manner.

1.1.2 Alzheimer's Disease

The most common ND is AD, affecting nearly 50 million patients worldwide [23]. Neuropathologically, AD results in synapse loss and neuronal atrophy which is identified using diagnostic criteria; specifically, an accumulation of amyloid plaques comprised of β-amyloid peptides (Aβ) and neurofibrillary tangles (NFTs) formulated from microtubule-associated protein tau (MAPT) [24]. Similar to PD, Aging is also an important risk factor for AD [24]. Although AD does primarily affect cognition, it has been recognized in the literature that cognitive decline does have a direct detrimental effect on physical function [BREIJYEH 2020]. Specific to impairments of physical function, AD patients commonly experience symptoms of muscular weakness and postural instability which increase the risk of falls in AD patients [25]. Therefore, AD has a negative impact on both a patient's cognitive and physical function, and in turn, patient QoL as the disease progresses.

1.1.3 Huntington's Disease

HD is a hereditary late-onset ND [26]. The exact causation of HD is due to mutation in the Huntingtin protein coded by the HTT gene [26]. Characterized by degeneration of the medium spiny neurons of the striatum, HD patients experience a general reduction in brain mass, cognitive decline, and encounter such symptoms as muscular atrophy, involuntary or slowed movements, postural instability, and muscular rigidity [26, 27]. Thus, movements like walking, standing, or other essential movements that support the performance of ADLs are severely and negatively affected by HD.

1.1.4 Amyotrophic Lateral Sclerosis

ALS is a late-onset ND that directly affects human movement and functional capabilities. Specifically, ALS is identified by an accelerated degeneration that is characterized by motor dysfunction and loss of the upper and lower motor neurons in the brain, brainstem, and spinal cord [28, 29]. ALS also affects both cognitive and physical function, resulting in progressive loss of motor control; and at end-stage diagnosis, patients have on average a three-to-five-year lifespan [28, 29]. Interestingly, during treatment of early-stage ALS, there exists approximately a nine-to-twelve-month window before diagnosis after onset [30]. With ALS cases expected to rise to around 380,000 patients worldwide by 2040, ND are an ever-present issue in relation to human movement and motor skill capability [28, 30].

1.2 Common Symptoms

Of the symptoms affecting motor control and physical function, three interrelated symptoms in particular stand out: 1) Muscular rigidity, 2) Muscular weakness, and 3) Muscular atrophy.

1.2.1 Muscular Rigidity

Muscular stiffness is a key symptom of NDs, defined as rigidity of the muscle tissue and correlated structures, resulting in a decrease in a patient's ROM about a joint [31]. Rigidity may affect a patient's balance and proprioceptive capability; which, in turn, may hinder the capacity to perform ADLs and affect the patient's QoL [31, 32]. Currently, rigidity is clinically identified using subjectively monitored scales like the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS), which is a three-part, Likert-scaled, questionnaire that takes approximately 30-minutes to complete [33]. During the testing protocol patients are not required to conduct movements, but answer subjective questions based on their recent experiences with conducting PA, ADLs, and basic human movement [34]. This does not mean that subjective scales or other qualitative measures are not valuable to the clinician, instead this provides a foundation whereby the development of supplemental technologies capable of assisting the clinician in both quantifying a patient's functional movement assessment and refining subsequent decisions regarding treatment plans and patient monitoring in clinic.

Rigidity of the lower limbs has been associated with frequent falls in ND patients [35]. Concurrently, axial rigidity has been found to be related to an increased risk of falls in ND patients [36]. Moreover, postural instability and muscle rigidity are both characterized by reductions in functional capacity, noticeable when performing simulated movement tasks [35]. Thus, observing and assessing deliberate movement while monitoring whole-body human motion in simple or complex tasks may prove beneficial while creating a risk-specific profile for the patient.

1.2.2 Muscular Weakness

Muscular weakness of an ND patient's upper and lower limbs will negatively impact QoL and ability to perform ADLs [37]. In ALS, up to 50-80% of the motor neurons can be lost due to degeneration leading to muscle wasting as a result of muscle weakness and loss of function [38]. Perceived weakness paired with abnormal sensation was found to be common in PD patients as well [39]. As muscle tissue progresses through each disease, composition changes are expected; however, investigations are currently ongoing, focused towards motor neuron survival through disease progression [40]. Thus, these investigations, when involving human movement, may benefit from supportive wearable motion sensor technology to assist in understanding underlying mechanisms and track human movement during protocol execution.

1.2.1 Muscular Atrophy

Muscular atrophy, otherwise known as muscle wasting, is defined as neuronal loss from disease-specific degeneration, resulting in motor dysfunction and is characterized by a loss of skeletal muscle tissue [41]. In ALS and HD, muscular atrophy is a distinctive characteristic of the disease progression of NDs that primarily affect the spinal cord motor neurons [27, 42, 43]. ND patients experiencing neuronal degeneration leading to muscular atrophy frequently encounter decreases in QoL and motor control [44]. Thus, ND patients are at greater risk of injury or fatality as their disease-state progresses.

1.3 Additional Considerations

NDs paired with issues related to aging and symptom-specific problems, lead to the potential for hospitalization or injury. Resulting in both a financial burden and potential physical ability reductions.

1.3.1 Falls and Injury Prevention

Currently, an estimated 75% of the hospitalizations in PD patients are due to either fall or fracture, and approximately 60% of the reported falls in PD patients are documented as related to, or resulting from, postural instability [45]. Concurrently, in AD, HD, and ALS, there is a documented higher incidence of falls and fractures [46]. Therefore, PD patients can benefit from early detection and monitoring of symptoms to ensure that multimodal treatment strategies are implemented to maintain motor functionality, which directly affects the ability to perform activities of daily living (ADLs) and thus bears impact upon the patient's QoL [47].

1.3.2 Exercise-based Intervention

Although AD does primarily affect cognitive function, cognitive decline has been evidenced to negatively influence physical function [48]. Specifically, a loss in axial muscular strength was found to be directly correlated to onset of AD [49]. Exercise participation has also shown to improve balance, proprioception, and muscle strength, while reducing fall risk in elderly patients [50]. Concurrently, regular engagement in exercise has been shown to provide a protective effect against age-related neurodegeneration while improving functional capabilities making ADLs easier and improving QoL in elderly ND patients [51]. Thus, the benefits of exercise participation are clear and evident in in the literature aimed at supporting longevity and healthy aging in elderly ND patients.

1.3 Applicable Technology

MOCAP technology has supported investigations involving the analysis of human movement [52]. These systems can be marker-based or markerless while tracking human movement [53]. Currently, the gold standard in movement analysis is 3-D MOCAP technology [54].

Although MOCAP systems can provide precise real-time data; the setups are complex and quite expensive, which directly limits accessibility and useability within the clinical setting [55]. For example, with the visual-optical nature of MOCAP technology, the OC3D device is recommended by the manufacturer, Northern Digital Inc., to be placed between two and six meters away from where human movement will be assessed [56]. Concurrently, MOCAP technologies like the OC3D require placement of reflective markers for tracking human movement [57]. Furthermore, the more cameras present, the more expansive the vision capabilities are for a given MOCAP system [58]. Meaning device placement and camera vision are critical for both accuracy and reliability of results and testing using MOCAP technology.

Alternatively, Kinovea is a free-to-use, video-based, 2-D movement analysis software that has been successfully validated against 3-D MOCAP technology [59]. Despite the ability to assess human movement in a cost-effective manner, Kinovea still has a high learning curve in reference to end-user familiarization; and being a 2D technology, discrepancies or loss of data while performing rotational movements in the transverse plane may occur depending on the movements performed and degree of rotation, unless extreme modification to the vision of the camera is made to improve visibility for data collection [60]. Thus, 2-D visual-optical technologies are a valuable alternative depending on the situational utilization requirements.

Wearable devices are small, minimally intrusive, and do not require complex setups like that of optical-based MOCAP technology. Specifically, IMU sensors can be combined into an integrated system providing the ability to support assessment of human motion for rehabilitation and training purposes [54]. To this point, some interventions have included wearable technologies intended to function supplementally in assessing both stationary balance and stability while walking between PD patients and a healthy control population [61]. However, since human movement occurs in a systematic manner; depending upon the needs of the analysis, a single IMU sensor, or multiple IMU sensors, may be used to visualize data sets while monitoring movements about a joint or limb segment [62]. Although the literature at present does feature some coverage on wearable motion technologies, there is still an associated need for more high-quality literature investigating novel and unique wearable motion technologies to provide quantitative evaluation in support to the existing qualitative clinical assessments [61].

IMU sensors contain a set of gyroscopes, accelerometers, and magnetometers; combined with the triaxial capacity of the accelerometers, movement data can be collected across all three planes of anatomical motion and documented via Bluetooth connectivity [63]. Concurrently, IMUs collect linear and angular data to determine positional displacement and spatial location of a joint or body in motion in real-time [64]. Furthermore, these devices are cost-effective, easy-to-obtain, and require minimal setup for functional assessment of human movement [54]. Thus, IMU sensors may hold some merit in supporting the quantification of data as a wearable tool to support the clinician during physical assessment of a PD patient.

1.1.1 Important Considerations

Physical activity (PA) in the form of dedicated times whereby meaningful exercise is conducted, specific to interventions involving resistance training (RT) and cardiorespiratory fitness (CRF), is now recognized as an important component towards management of PD [63]. Additionally, interventions combining both cognitive and physical tasks into a dual-task activity showed significant reductions in fall risk comparative to traditional physical therapy [66].

2 Preliminary Work

To assess the utility and functionality of using a single IMU device, a test case was conducted to determine the efficacy of using an IMU device, when compared to the OC3D, in capturing movement.

2.1 Data Collection

One participant was used in this test case to provide proof of concept for the proposed methodology. The IMU device (3D Joint ROM sensors, Shemesh Health Solutions, South Africa) and OC3D (Optotrak, NDI Digital, Canada) are shown below in Fig. 1.

Fig. 1: Device images.

A B

The OC3D and IMU sensor devices are shown in Fig. 1A and Fig. 1B, respectively.

Device setup was designed to ensure accurate collection of data while wearing components specific to each device, simultaneously. The participant was outfitted with both the IMU and the reflective markers for the OC3D and then positioned approximately two meters from the OC3D tower. Additionally, to minimize errors, the IMU sensor was placed at the back of the head, while the OC3D reflective markers were placed at the forehead in line of sight for the OC3D tower. An image of the device setup is shown below in Fig. 2.

Fig. 2: Image of device setup.

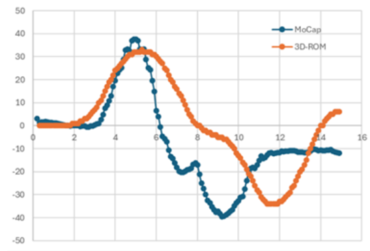
The device setup including the OC3D tower, OC3D reflective markers on the forehead, and the IMU at the back of the head.

The participant was asked to perform one repetition of each of the following movements: 1) Cervical flexion-extension, 2) Cervical lateral flexion, and 3) Cervical rotation. Data on cervical flexion-extension was recorded and used for this test case, all other data was cataloged and stored for later use.

2.2 Results

Findings from reviewing the preliminary data were that the OC3D and IMU collected data held some similarity while assessing motion. The data collected is shown in Fig. 3 below.

Fig. 3: Cervical Flexion-Extension motion data comparison.



Data shows clear and definitive motion tracking from the IMU sensor through full movement comparative to what was collected by the OC3D device.

As can be seen in the preliminary data, there is minor variability within the OC3D data. Specifically, during cervical extension, the Optotrak lost track of the reflective markers partially, thus an equipment-specific limitation was confirmed and identified for the OC3D. This limitation being that the device, as a visual-optical technology, requires complete and constant "line-of-sight" on the reflective markers. Leading to the conclusion that the OC3D tower, by itself, is insufficient when compared to the IMU device. Thus, the OC3D will require a multiple-camera setup to operate effectively to capture a full view to model human movement.

3 Discussion

IMU devices uniquely are able to track kinetic and kinematic data, and these devices are exceptionally positioned as a viable technology for human motion assessment in ND patients [11, 55]. At the forefront of therapeutic intervention in relation to human movement dysfunction is the concern for ND patients and their ability to perform ADLs [6].

Due to the multifactorial limitations resultant from ND symptoms, regular movements of walking, bending, or reaching may become restricted and difficult [6]. The combination of balance, gait, and postural impairments in ND patients has led to the proposal of investigating axial disturbances for early identification of such key symptoms as axial immobility [67]. Thus, these reductions in ROM at joints across the whole body hold a direct impact on the patients ability to perform ADLs and, in turn, their QoL.

The severity of impact on everyday activities and QoL affected by ND-specific motor dysfunction is both a neurological and aging issue. Interventions involving RT and CRF have shown favorable results that PD patients can benefit from regular planned exercise participation to support symptom management, longevity, and systemic health [68, 69]. Although the OC3D and other visual-optical MOCAP systems are considered the gold-standard; these technologies have several barriers to being used within the clinical setting for human movement assessment. Practically speaking, IMU sensors are cost-effective, wearable, and can support quantitative testing and clinical applications for ND patient functional assessment strategies. Thus, further research should be conducted on the use of IMU sensor technology while conducting relevant biomechanical assessments with ND patients to assess the validity and reliability of data collected from a gold-standard MOCAP system versus an IMU sensor system to provide clinicians with relevant information for making a sensible decision on obtaining and implementing such technology in their clinical protocols.

4 Conclusion

IMUs are miniature, wearable sensors that represent a cost-effective technology. Their ease of use and applications for movement assessment make IMU devices a veritable and recommended technology for clinical applications. The potential of this technology for providing baseline head/neck movement data of ND patients and tracking movements over time warrants further investigation in this population. Future research examining the reliability and validity of IMUs for head/neck movements can support efforts in improving early-stage outcomes and providing timely interventions for ND patients.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.