Toward a Multi-Modal Brain-Body Assessment in Parkinson's Disease: A Systematic Review in fNIRS

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***Abstract*—Parkinson's disease (PD) causes impairments in cortical structures leading to motor and cognitive symptoms. While common disease management and treatment strategies mainly depend on the subjective assessment of clinical scales and patients' diaries, research in recent years has focused on advances in automatic and objective tools to help with diagnosing PD and determining its severity. Due to the link between brain structure deficits and physical symptoms in PD, objective brain activity and body motion assessment of patients have been studied in the literature. This study aimed to explore the relationship between brain activity and body motion measures of people with PD to look at the feasibility of diagnosis or assessment of PD using these measures. In this study, we summarised the findings of 24 selected papers from the complete literature review using the Scopus database. Selected studies used both brain activity recording using functional near-infrared spectroscopy (fNIRS) and motion assessment using sensors for people with PD in their experiments. Results include 1) the most common study protocol is a combination of single tasks. 2) Prefrontal cortex is mostly studied region of interest in the literature. 3) Oxygenated haemoglobin (HbO_2) concentration is the predominant metric utilised in fNIRS, compared to deoxygenated haemoglobin (HHb). 4) Motion assessment in people with PD is mostly done with inertial measurement units (IMUs) and electronic walkway. 5) The relationship between brain activity and body motion measures is an important factor that has been neglected in the literature.**

***Index Terms*—Brain activity assessment, functional near-infrared spectroscopy (fNIRS), gait assessment, motion assessment, Parkinson's disease (PD).**

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List of Abbreviations

PD	Parkinson's Disease.
fNIRS	Functional Near Infrared Spectroscopy.
M1	Primary motor cortex.
MDS-UPDRS	Movement Disorder Society Unified Parkinsons Disease Rating Scale.
FoG	Freezing of gait.
IMU	Inertial measurement unit.
CoP	Center of pressure.
HHb	Deoxygenated haemoglobin.
ML	Machine learning.
fMRI	Functional magnetic resonance imagery.
PFC	Prefrontal cortex.
SMA	Supplementary Motor Area.
PMC	Premotor Cortex.
HbO_2	Oxygenated haemoglobin.
DLPFC	Dorso-lateral Prefrontal Cortex.
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses.
ROI	Regions of interest.
H&Y	Hoehn and Yahr scale.
NT	Neurotypical.
EEG	Electroencephalography.

I. Introduction

PARKINSON'S disease (PD) is the second most common neurodegenerative disorder of the central nervous system, with millions of people worldwide suffering from this condition [1]. This disease affects nerve cells in the brain responsible for body movement. PD causes uncontrollable movements, including tremor, muscle rigidity, and difficulty with balance and coordination [2]. Almost 80% of people with PD eventually develop freezing of gait (FoG), which is characterised by brief episodes of inability to initiate or continue walking [3]. In addition to FoG, postural instability is another important symptom of PD. These two symptoms contribute to a gait disorder, and postural impairment, and in turn may cause falling in people with PD [4]. Gait impairments in people with PD are exacerbated when performing a simultaneous cognitive task while walking known as dual-task walking. During dual tasking, the requested additional attention load affects the patient's motor

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functions, and in turn may cause an increased risk of falls, reduced functional capacities, leading to disabling consequences during daily life activities [5], [6]. All these complications make PD a critical clinical issue. However, research shows that the early-stage diagnosis leads to positive results in the management of PD symptoms [7].

Monitoring the progression of PD can provide clinicians and physical therapists with valuable information regarding changes in motor performance [7]. Various clinical scoring systems and tools have been developed for the evaluation of symptoms and disease severity in people with PD. For instance, the Movement Disorder Society-Unified Parkinson's Disease Rating Scale (MDS-UPDRS), and the Hoehn and Yahr scale (H&Y) are standard clinical rating scales for the diagnosis and specification of the disease stage [8]. Most of these scales and scores are well-known and widely used in clinical practice. However, these clinical ratings are subjective and have limitations regarding accurate measures of the symptoms [9], [10]. For instance, in a study by Mancini et al. [11], it was observed that PD patients experienced a gradual decline in their postural control over a period of 12 months when assessed using quantitative measurements. In contrast, no changes were evident in the motor section (III) of the UPDRS over the same time frame. These findings indicate that objective measurements of postural sway may be more effective in detecting changes and are more sensitive compared to scores obtained from the UPDRS III [12]. In addition, some of these evaluation tools are time-consuming and require lengthy processing time [9]. Therefore, there is a vital need for objective and accurate assessment methods of PD symptoms.

Objective assessment of PD involves utilising specific tests and measures to evaluate various aspects of the patient's condition such as their motor symptoms. Motor symptom assessments such as gait or tremor assessment can be conducted using sensors [13]. Several technologies are used to assess motor function in individuals with PD, including wearable sensors such as inertial measurement units (IMUs) and non-wearable technologies or ground platforms such as force-plate [13]. These sensors could be used to monitor the disease progression quantitatively, provide unbiased measurements, and enable detection of subtle changes that would otherwise go unnoticed [9]. Although sensor-based assessment of motor symptoms in PD has provided valuable insights into the literature, there is a growing interest in exploring various modalities for PD assessment and diagnosis.

In addition to physical symptom assessment, neuroimaging has been proposed as a potential marker in early-stage PD [14]. These techniques can provide an indirect reflection of the neural impairments that contribute to motor alterations [14]. Neuroimaging techniques have traditionally been used to study brain structure and function. Assessment of brain activation patterns of people with PD during movement can advance the understanding of potential cortical mechanisms associated with underlying motor impairments in this cohort of people [15]. Various neuroimaging techniques such as functional magnetic resonance imagery (fMRI), electroencephalography (EEG), and functional near-infrared spectroscopy (fNIRS) have been used to investigate changes in brain activation in people with PD [16]. Compared to other methods, fMRI exhibits superior spatial resolution [17]. However, fMRI is highly susceptible to movement artifacts and not portable, which makes the recording of changes in brain activation during walking impossible [18]. Portable technologies such as EEG or fNIRS are preferred in applications for real-time monitoring that involve movement tasks like walking. While EEG has better temporal resolution compared to fNIRS, it has relatively lower spatial resolution [16]. This limits its ability in discriminating between brain regions with greater accuracy [19]. In this context, fNIRS offers better spatial resolution allowing for more accurate identification of the activated cortical areas, and is also less sensitive to movement artifacts than EEG [16]. fNIRS has been a widely used technique for recording brain activation patterns in patients with gait disorders, and PD [15], [20]. Therefore fNIRS has been recognised as a promising tool for understanding the contribution of cortical areas during movement activities [16].

There has been an increasing interest in studies that involve multi-modal assessment of body movements and brain activity in the literature, in order to explore the relationship between the two [21], [22]. Several studies have investigated the coupling between brain activity and body motion in people with PD [23], [24], [25]. Combining multiple assessment systems can help to address the limitations of each individual system, leading to more robust and accurate parameters [26], [27]. Motor symptom measures in conjunction with neuroimaging techniques could help in better understanding the PD progression, monitoring treatment response, and developing novel therapeutic interventions, as well as finding the interaction between cortical activity and body movements [21]. Furthermore, the combination of physical symptoms assessment technologies and neuroimaging techniques could facilitate the evaluation of motor impairments during dual-tasking situations that involve higher cognitive loads in individuals with PD. In order to gain a better understanding of the recent findings in this field and identifying existing limitations, a more focused review of the literature is necessary.

This article aims to explore the impact of PD on brain activity, body motion, and balance, as well as the interplay between these factors. Specifically, we examined studies that employ fNIRS for brain activity recording and motion assessment devices (i.e., sensors) for balance and movement measurements in individuals with PD. This review provides insights into the methods used for assessing brain activity and body movements, the metrics for these assessments, regions of interest for brain activity recording, and the correlation between brain activity and body motion measures. To identify the most significant limitations and findings in the literature, we conducted a search of existing literature reviews in the field, which is discussed in the following subsection. The findings of this review can guide future studies in the utilisation of objective metrics for PD assessment and diagnosis.

A. Related Works

Among the published literature, there are five related review papers that explore the relationship between brain activation and motion assessment. Table I shows a summary of these articles, including their aims and limitations with respect to the aim of this study. These review papers have brought considerable knowledge into the literature by comparing the existing studies in several aspects. Some of these review studies do

TABLE I
SUMMARY OF THE REVIEW PAPERS IN THE FIELD

Author & Publication Year	Aim of study	Number of papers	Time Period	Limitations
Stuart *et al.* [13] 2018	Examining cortical activity during walking and balance tasks in older adults and in people with Parkinson's disease, using functional near-infrared spectroscopy (fNIRS) or electroencephalography (EEG)	37	2009-2017	Focus of the study is not objective motion assessment. Cohort of participants does not focus on people with PD. Since its publication, numerous articles have been published that may provide additional insights into the topic.
Pelicioni *et al.* [14] 2019	Summarising the research regarding Prefrontal cortical (PFC) activation patterns during simple and complex walking tasks in young adults, older adults, and clinical groups with balance disorders using fNIRS.	35	2004-2018	Focus of the study is not objective motion assessment. In addition, considered motion and balance tests are limited in this study Cohort of participants does not focus on people with PD. Since its publication, numerous articles have been published that may provide additional insights into the topic.
Udina *et al.* [15] 2020	Describing the use of fNIRS to study frontal lobe heamodynamics during cognitive, motor and dual-tasks in older adults	46	2013-2018	Focus of the study is not objective motion assessment. Cohort of participants does not focus on people with PD.
Sun *et al.* [16] 2020	Summarising the research on FoG computing in sensor selection, feature extraction, algorithms, and performance	29	2008-2019	Focus of this study is movement assessment only, brain activity is not considered.
Lin *et al.* [17] 2021	Explores the neural mechanisms of cerebral heamodynamic responses using fNIRS to the difficulty level of ambulatory tasks (walking and turning) in persons with PD	10	2016-2021	Focus of the study is not objective motion assessment.

TABLE II
RESEARCH QUESTIONS

Question	Objective
RQ1: In relation to the use of fNIRS in people with PD, what motor assessments are commonly undertaken? RQ2: What motion sensors and metrics are more useful in PD assessment in fNIRS studies?	Aim 1: Suitable balance and motion assessment in addition to fNIRS for PD.
RQ3. Which brain areas have been examined in fNIRS studies for people with PD? RQ4. What fNIRS metrics are more useful in studying PD?	Aim 2: How fNIRS is used with regards to PD.
RQ5. What is the most appropriate way to assess the motion and balance measures using sensors and the brain activity measures using fNIRS together?	Aim 3: How to combine the motion and brain activity for objective PD assessment.

not focus on objective body motion assessment, however, they have considered brain activity recording. For instance, Stuart et al. [15] reviewed the activity of cortical areas in older adults and persons with PD while walking and conducting balance tasks. However, they did not focus on objective motion assessments and their cohort included people without PD. Similarly, the three other review studies did not consider objective motion assessment in their review. On the other hand, Sun et al. [30], focused on motion assessment methods and sensors, however, they did not consider the brain recording along with their study protocol. While all these review articles have addressed various effective aspects of brain activity or body motion assessments in people with and without PD, none of them have studied both brain activity and body motion assessment of patients with PD.

II. METHODOLOGY

A. Research Questions

This research study aimed to investigate the relationship between brain activity and body motion/balance in people with PD to look at the feasibility of PD assessment/diagnosis using these objective metrics. The research questions are outlined in Table II. To achieve our objectives and answer our research questions, firstly, this study focused on finding suitable balance and motion assessment tests in conjunction with fNIRS for persons with PD. Moreover, we studied the sensor types used for the movement assessment of PD people. Secondly, we looked at the reported fNIRS setting and its haemoglobin signals in the literature for people with PD. Lastly, this study aimed at exploring the relationship between brain activation and body motion assessments for this cohort of patients.

B. Search Strategy

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statements [32] to identify and screen the articles included in this systematic review. The search was conducted in December 2022 using Scopus as our database. We used the following Keywords: ((((((near AND infrared AND spectroscopy) OR functional AND near

TABLE III
SUMMARY OF COHORT DEMOGRAPHICS IN THE REVIEWED STUDIES

Author	Participants Cohort, Male/Female	Age† Average ± SD (year)	Disease Duration (year)	UPDRS III score	Medication Status	Moca/MMSE* Score
Maidan *et al.* [46]	PD (8M/3F) HC (4M/7F)	66.2±10 71.2±6	5.6± 3.1	OFF: 35.2 ±11.3 ON: 27.7 ± 11.4	ON/OFF	—
Mahoney *et al.* [40]	PD (11M/15F) MPD (50M/67F) HC (57M/69F)	81.23±5.93 77.50±6.72 74.41±6.12	—	—	—	—
Nieuwhof *et al.* [48]	PD: 7M/5F	70.1 ± 5.4	5.7 ± 3.3	—	ON	* 27.4 ± 2.0
Maidan *et al.* [52]	PD: 46M/22F HC: 20M/18F	71.6 ± 0.9 70.1 ± 5.4	9.1±0.7	32.9 ± 1.7	ON	* 28.2 ± 0.2 28.8± 0.2
Maidan *et al.* [45]	PD:33M/16F	72.8 ± 1	9.7± 0.9	31.8 ± 2.1	ON	* 28.5 ± 0.2
Maidan *et al.* [53]	PD(TT): 23M/11F PD(TT+VR): 22M/8F	73.1 ± 1.1 70.1 ± 1.3	9.7 ± 1.0 8.9 ± 1.1	32.6 ± 2.1 33.9 ± 3.1	ON	* 28.3 ± 0.3 28.2 ± 0.3
Thumm *et al.* [36]	PD: 10M/10F	69.8 ± 6.5	7.48±4.15	27.26± 12.44	ON	26.9 ± 2.34
Klempir *et al.* [44]	PD: 8M/1F	65 ± 6.3	—	DBS STN OFF: 53.4 ± 11 DBS-STN ON: 29.1 ± 11.5	OFF	—
Belluscio *et al.* [34]	PD+FoG:13M/4F PD-FoG:11M/4F HC:5M/3F	69.9 ± 4.3 69.9 ± 5.0 66.5 ± 5.5	13.5± 6.0 9.35± 6.7	46.9 ± 11.8 33.5 ± 11.2	OFF	28.7 ± 1.3 25.4 ± 3.8 26.6 ± 1.9
Stuart and Mancini [54]	PD:17M/8F	69.20±3.99	10.00 ±6.27	36.40 ± 11.67	OFF	27.12 ± 3.83
Abtahi *et al.* [21]	PD:5M/6F HC: 3M/7F	74.54±7.58 66.1 ± 7.31	5.7± 5.6	—	—	—
Orcioli-Silva *et al.* [49]	PD:15M/5F HC:15M/15F	69.8 ± 5.9 68.0 ± 5.6	5.6 ± 3.1	OFF: 35.2 ± 11.3 ON: 27.7 ±11.4	ON/OFF	* 26.9 ± 1.8 27.7 ±1.6
Sharon *et al.* [43]	PD:20M/14F HC:15M/11F	67.41±5.74 71.35±8.87	3.5	27.0	ON	27.00 26.50
Vitorio *et al.* [50]	PD+FoG:16M/8F PD-FoG:18M/5F	70.3 ± 4.7 70.8 ± 7.6	10.1 ± 6.1 7.2 ± 5.2	42.4 ± 13.2 35.0 ± 10.3	OFF	26.0 ± 3.1 27.2 ± 3.7
Jang *et al.* [37]	PD (Itvn):10M/3F PD (Ctrl):7M/6F	65.38±7.81 61.46±8.33	6.92 ± 4.83 8.38 ± 3.88	—	ON	—
Ranchet *et al.* [18]	PD:11M/7F HC:11M/7F	68 ± 8 66 ± 7	5	17	ON	27.5 27
Dagan [25]	PD:33M/7F	68.38±7.48	8.83 ± 5.52	OFF: 42.25 ± 14.37 ON: 35.25 ± 13.45	ON/OFF	* 28.4 ± 1.7
Bretta [35]	PD: 14M/10F	68.91±8.47	4.84 ± 3.11	36.00 ± 14.32	ON	* 27.00 ± 2.00
Orcioli-Silva *et al.* [24]	PD: 18M/5F HC:15M/15F	70.55±6.03 67.99±5.61	5.26 ± 3.08	OFF: 37.70 ± 12.16 ON: 29.91 ± 11.95	ON/OFF	* 26.57 ± 2.02 27.67 ± 1.60
Vitorio *et al.* [51]	PD:14M/6F	72.68±7.58	7.63 ± 4.78	OFF: 41.9± 10.54	ON	25.95 ± 2.99
Conceição *et al.* [38]	PD: 10M/10F	70.80±7.87	6.37 ± 3.44	36.84 ± 14.31	ON	26.57 ± 1.89
Pelicioni *et al.* [47]	PD:33M/16F HC:13M/8F	69.7 ± 7.8 69.0 ± 5.9	6.8 ± 4.8	31.6 ± 10.1	ON	28.8 ± 1.3 29.0 ± 1.1
Hoang *et al.* [39]	PD:10M/4F	67 ± 9	6 ± 5	21.57 ± 11.65	ON	26.9 ± 1.9
Maidan *et al.* [23]	PD: 98M/51F HC:30M/27F	69.81±7.68 68.88±7.81	8.27 ± 5.51	30.56 ± 13.57 3.46 ± 4.51	ON	24.6 ± 3.68 26.75 ± 2.56

Abbreviations. PD: Parkinson's Disease. HC: Healthy Control. †: Ages in each line belongs to same cohort of that line in previous column. *: MMSE score. MPD: mild Parkinsonian sign. TT: Treadmill training. TT+VR: Treadmill training plus virtual reality. FoG: Freezing of Gait. Itvn: Intervention. PIGD: Postural instability gait disorder. TD: tremor dominant. PD+FoG: PD people with FoG. PD-FoG: PD people without FoG.

AND infrared AND spectroscopy) OR nirs) OR fnirs) AND (gait OR walking OR locomotion OR turning OR standing OR stepping OR movement OR motion OR balance OR (postural AND sway)) AND (Parkinson OR (PD)))) for our search. The initial search yielded 75 articles.

C. Selection Criteria

The screening was conducted by one person and cross-checked by two reviewers. Inclusion criteria for review were as follows: Publication year was fixed to last ten years (2012-2022). The subject area was limited to Engineering, Medicine, and Neuroscience. Papers only in the English language were included. Initially, five papers without Parkinson's disease keywords in the title or abstract were excluded (Fig. 1). Then, the abstracts, case studies, reviews, commentaries, discussion papers, editorials, or conference proceedings were excluded from the list. The extracted review papers were considered separately to find the limitations of previous works.

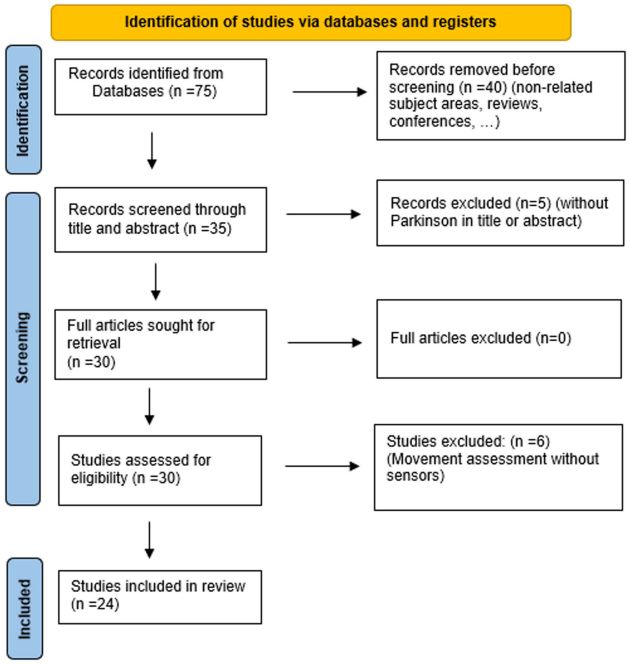

Fig. 1. PRISMA flow chart of study design. This illustrates the yield of the search strategy at each stage of the study selection process.

At the next stage after a comprehensive screening of the title, abstract, and full text, papers were excluded if: 1. they had not considered fNIRS for brain activity recording, 2. the recruited participants in these studies were not people with PD, and/or 3. quantitative motion assessment using motion sensors had not been considered in the study. At the end of the review process, 24 papers remained for further review.

D. Data Extraction

Data were extracted and synthesised into tables by one person and confirmed by two other reviewers. The extracted information comprised participants' general and pathological characteristics (e.g. age, disease stage, medication status), motion assessment tasks (e.g. usual walking, dual-task walking, standing, turning), fNIRS data (oxyhaemoglobin, activation area), motion sensor types (e.g. wearable IMUs, electronic walkway, force plates), and correlation between brain activation and body motion assessments of the studies.

III. RESULTS

All 24 selected studies have been summarised and presented in Table IV. The included papers are categorised based on the main aim of this study which is objective brain activity and body motion assessment in people with Parkinson's disease (PD). Therefore, factors that are described here include movement assessment tasks, brain regions of interest (ROI), motion assessment sensors, fNIRS haemoglobin signals, and the correlation of fNIRS and motion measures. These categorisations were performed with the aim of finding answers to our objectives which are: 1) appropriate motion assessment tests and motion sensor type and placement for PD, 2) useful fNIRS setting, and

TABLE IV
SUMMARY OF THE REVIEWED STUDIES INCLUDED IN THIS LITERATURE REVIEW

Author [Year]	Application of Study	Test Protocol	Dual Tasks	Motion Outcome Measures	fNIRS Data	ROI	Number of Sensors: fNIRS,IMU	Measured Activity with fNIRS	Sensor Type and Placement	Relation Between fNIRS and Motion Measure
Maidan *et al.* [46] 2015	PD assessment	Simple walking/Turning in place	—	Acceleration, No. of turns, Turn duration	HbO_2* HHb	PFC	6 Ch, 1 IMU	PD+FoG: Turning (↑)	IMU, Lower back	—
Mahoney *et al.* [40] 2016	PD assessment	Standing	—	CoP velocity	HbO_2	PFC	16 Ch, —	PD: Standing (↑)	Walkway	—
Nieuwhof *et al.* [48] 2016	PD assessment	Simple Walking	Serially subtracting/ Reciting digit spans	Gait speed, Cadence, Stride length, Stride time	HbO_2 HHb	PFC	6 Ch, —	PD: walking while serially subtracting (↑)	Walkway	—
Maidan *et al.* [52] 2016	PD assessment	Simple Walking/Obstacle Avoidance	Serial subtraction	Gait speed, Stride length	HbO_2* HHb	PFC	6 Ch, —	PD: Walking / Obstacle negotiation (↑) HC: Dual-task Walking (↑)	Walkway	Positive correlation between level of HbO_2 and gait speed
Maidan *et al.* [45] 2017	PD assessment	Simple Walking/Turning in place	—	Gait speed, Stride length	HbO_2* HHb	PFC	6 Ch, —	PD: Walking (↑) PD: Turning (↓)	Walkway	Inverse correlation between level of HbO_2 and gait speed
Maidan *et al.* [53] 2018	Pre-post intervention PD assessment	Simple Walking/Obstacle Avoidance	Serially subtracting	Gait speed, Stride length	HbO_2	PFC	6 Ch, —	Before-training: All tasks (↑) After-training: All tasks (↓)	—	
Thumm *et al.* [36] 2018	Pre-post intervention PD assessment	Simple Walking	—	Gait speed, Stride time	HbO_2	PFC	—, 3 IMU	PD: Treadmill walking (↑)	IMU, Lower back and Ankles	—
Klempir *et al.* [44] 2019	Pre-post intervention PD assessment	Simple Walking/Hand movement	—	Gait speed, Cadence, Stride length, FT frequency, Power of FT, MOV	HbO_2 HHb	Whole Cortex	22 Ch, —	Finger tapping: Contralateral Motor cortex (↑) Walking: near longitudinal fissure (↑)	Walkway	—
Belluscio *et al.* [34] 2019	PD assessment	Turning in place	Auditory Modified AX-Continuous Performance Task	Duration of turn, Turn peak angular velocity, Angular rotational rate	HbO_2 HHb	PFC	8 Ch, 8 IMU	PD+FoG: Turning (↑) PD-FoG/ HC: Dual-task Turning (↑)	IMU, Sternum and pelvis levels, Wrists, Shanks, Feet	Positive correlation between level of HbO_2 and FoG Ratio for PD+FoG/ Inverse correlation between level of HbO_2 and number of turns completed for PD - FoG
Stuart and Mancini [54] 2020	Pre-post intervention PD assessment	Simple Walking/Turning in Place	AX-Continuous Performance Task	Speed, Foot strike angle, Stride time, Stride length	HbO_2	PFC	2 Ch, 8 IMU	PD: Early Walking (↑) PD: During turn (↑)	IMU, Feet, Shins, Lumbar, Sternum, Wrists	No consistent relationships between level of HbO_2 and measured features of gait
Abtahi *et al.* [25] 2020	PD Detection	Hand movements/Foot stomping	—	—	HbO_2* HHb	PFC	16 Ch, 17 IMU	—	IMU,Hand, Foot, Arm, Leg	—
Orcioli-Silva *et al.* [49] 2020	Pre-post treatment assessment	Simple Walking	Digit vigilance task	Step length, Step width, Step time, Step velocity	HbO_2	PFC	8 Ch, —	PD (ON): Dual-task (↑) HC: Dual-task (↑)	Walkway	—
Sharon *et al.* [43] 2020	PD assessment	Simple Walking/Obstacle Avoidance	—	Gait speed, Step length	HbO_2 HHb	PFC	8 Ch, —	PD: Obstacle Avidance (↑)	Walkway	Positive correlation between level of HbO_2 and obstacle negotiation performance
Vitorio *et al.* [50] 2020	PD assessment	Simple Walking/Turning in place	Auditory Modified AX-Continuous Performance Task	Gait speed, Stride length, Foot strike angle, Step time	HbO_2 HHb	PFC	8 Ch, 8 IMU	PD+FoG: Single/Dual-task Walking (↑)	IMU, Sternum and pelvis levels, Wrists, Shanks, Feet	Positive correlation between the level of HbO_2 and FoG severity, and step time variability during dual-task walking
Jang *et al.*2020 [37]	Pre-post intervention PD assessment	Simple Walking	—	Velocity, Cadence, Stride length, Stride time	HbO_2	Whole Cortex	—,—	Int (SMA and PFC): Walking (↑)	Walkway	Positive correlation between level of HbO_2 and swing, and single support times
Ranchet *et al.* [22] 2020	PD assessment	Simple Walking/Standing	Subtracting/ Counting forward	Gait speed, Cadence, Stride length, Gait time	HbO_2 HHb	DLPFC	14 Ch, 2 IMU	PD (DLPFC): Single/ Dual-task Walking (↑)	IMU, Shoes	—
Dagan [29] 2020	Pre-post treatment assessment	Simple Walking	Serial subtraction task	Gait speed, Step length, Stride time	HbO_2	PFC	2 Ch, 3 IMU	PD (ON): Single-task Walking (↑) PD (OFF): Dual-task Walking (↑)	IMU, Ankles, Lower back	—
Bretta [35] 2020	Pre-post intervention PD assessment	Standing	—	Recovery time, range of CoP, peak of the CoP velocity	HbO2	PFC	—, —	PD (Stimulated Hemisphere): Standing (↓)	Force Plate	—
Orcioli-Silva *et al.* [28] 2021	Pre-post treatment assessment	Simple Walking/Obstacle Avoidance	—	Step length, Step duration, Step velocity	HbO_2	PFC	8 Ch, —	PD (OFF): Obstacle Avoidance (↓) PD (ON)/ HC: Obstacle Avoidance (↑)	Walkway	Negative correlation between HbO_2 level and step length variability during unobstructed walking/ Positive correlation between HbO_2 level and step time variability, and step length variability during obstacle avoidance
Vitorio *et al.* [51] 2021	Pre-post treatment assessment	Turning in Place	Auditory Modified AX-Continuous Performance Test	Turns average peak speed, Turns Jerkiness, Fluidity of turning	HbO_2	PFC	8 Ch, 8 IMU	PD (levodopa + donepezil): Dual-task Turning (↓)	IMU, Sternum, Pelvis, Wrists, Shanks, Feet	—
Conceição *et al.* [38] 2021	Pre-post intervention PD assessment	Simple Walking	—	Step length, Step width, Step time, Step velocity	HbO_2 HHb	PFC	8 Ch, —	PD (Stimulated Hemisphere): Walking (↑)	Walkway	—
Pelicioni *et al.* [47] 2022	PD assessment	Simple Walking/Obstacle Avoidance/Target Stepping	—	Step length, Step velocity	HbO_2 HHb	DLPFC, SMA, PMC	17 Ch, —	PD (PMC): All Tasks (↑) HC (DLPFC): Obstacle Avoidance (↑)	Walkway	—
Hoang *et al.* [39] 2022	PD assessment	Simple Walking	—	Cadence, Stride length, Stride time	HbO_2* HHb	DLPFC	10 Ch, 2 IMU	PD (DLPFC): After Training (↓)	IMU, Foot	Positive correlation between HbO_2 level and stride length after training
Maidan *et al.* [27] 2022	PD assessment	Simple Walking	Serial 3 subtractions	Gait speed, Stride time	HbO_2* HHb	PFC	8 Ch, 3 IMU	PD: Walking (↑) HC: Dual-task walking(↑)	IMU, Ankles, Lower back	No consistent correlations between HbO_2 level and gait performance

Abbreviations. (PD): Parkinson's Disease. (ROI): Region of Interest. (Ch): Channel,(*):in those studies with HbO_2 and HHb measurement, only HbO_2 has been analysed. (MOV: Maximum opening velocity). (PD+FoG): PD people with FoG (assessed using new FoG questionnaire). (PD-FoG): PD people without FoG. (HC): Healthy control group. (↑): Increased Or higher HbO_2. (↓): Decreased or lower HbO_2. (Int): Intervention group. (ON): ON medication state. (OFF): OFF medication state.

3) exploring the relationship between brain activity and body motion assessment. In addition to these findings participants' medication status was also recorded. All of these items have been described in the following sections.

A. Movement Assessment Tasks

There are a number of standard movement and balance tests suggested for objective motion assessment of persons with PD used in conjunction with fNIRS in the literature [33]. These standardised motor tasks reflect the characteristics of certain PD symptoms and are introduced to explore differences between healthy controls and people with PD, as well as pre and post-treatment changes. The common movement tests used for motor performance assessment in older adults and people with PD include walking tests for gait analysis, standing tests to look at the postural balance performance, turning tests for measuring turn features, and various tests for measuring hand movements [21], [25], [34], [35]. Each of these tests measures a particular motor symptom in people with PD. Moreover, several studies have further investigated the link between cognition and motor control using dual-task paradigms, which assess the ability to execute two tasks simultaneously. In many cases, a motor task such as walking is combined with a cognitive task, like serial subtraction. For a better understanding of these tests, the movement assessment tasks that were carried out in each reviewed article have been categorised in this study. Grouping was based on single tasks, dual tasks, and a combination of single and dual tasks. Based on our review, the majority of studies have a single task in their movement assessment protocol (n=13). While there was only one paper (n=1) considering dual-task walking for motion assessment, several studies used both single and dual tasks in their experiments (n=10).

1) Single Task: The mostly used protocol for the assessment of movement in patients with PD is a single task (54% of reviewed studies). To study the physical symptoms of PD, different single tasks have been used in the literature, including simple walking tests (treadmill walking, unobstructed walking, and overground walking), balance tests (standing), arm and hand movement tests (finger tapping, hand flipping, arm movement), turning in place, and complex walking tests (walking and obstacle avoidance, walking and turning in place). Results obtained from these movement assessment tests depend on various factors based on the aim of the studies, such as considered symptoms, interventions that have been examined, number of participants, and their disease stage.

Studies that have simple walking as a single task in their study protocol, examined gait features e.g. step time and length,

cadence, and stride velocity of people with PD with different interventions such as stimulation, exercise, and medications. For instance, Thumm et al. [36] assessed the gait measures of the participants with PD during usual overground walking and walking on a treadmill. Since gait disorder is one of the important motor symptoms in people with PD, their aim of examining two walking conditions was to compare the effect of these training sessions on the performance of their gait with respect to fixed and variable paces. Jang et al. [37] measured the gait features of PD participants during a 10-m walk test to analyse the effect of acupuncture treatment. Conceição et al. [38] examined gait in people with PD during overground walking pre and post-intervention. Hoang et al. [39] studied the effect of exercise-based training sessions on the gait of a group of PD participants during a simple walking task. In summary, all of these studies used simple walking in their motion assessment to analyse gait impairment in different situations caused by PD and the results are different based on their aim of research and interventions.

Among the reviewed articles, there are some studies that have motor tasks other than walking as their single task for movement assessment. These tests include hand and arm movements, and standing tests. One of the reviewed studies focused on hand and arm movements that consisted of finger tapping, arm movement, and hand flipping [21]. Studies measuring hand and arm movements in people with PD mainly aim at assessment of hand tremor. Moreover, a few studies (n=2) examined postural sway features while performing a standing test [35], [40]. During quiet standing, the human body experiences postural sway which may increase due to aging or as the effect of some diseases [41]. Postural instability in people with PD affects postural sway. Thus sway assessment can help with further understanding of this PD physical symptom [42]. Overall, considering PD impairments in each study, there are various movement and balance measures used in the literature examining fNIRS in people with PD.

Since PD is a multi-symptom disease affecting various body segments, few studies examined movement in PD subjects with two different single motor tasks. During the performance of challenging tasks such as walking while crossing an obstacle, greater cognitive functions for motor planning, working memory, and inhibition is used [43]. For instance, Klempir et al. [44] assessed finger tapping in addition to gait of PD participants in their experiments. Maidan et al. [45], [46] studied the movement of people with PD with freezing of gait (FoG) during turning and usual walking. Turning is usually used for FoG assessment in PD. Orcioli-Silva et al. [24] assessed motion measures of PD people during unobstructed walking and obstacle avoidance to look at the effect of difficulties due to different motor tasks for this group of people. According to Sharon et al. [43], various types of obstacles in their protocol resulted in different activation patterns in people with PD. In a study by Pelcioni et al. [47], they examined a group of PD and healthy age-matched people while simple walking and three random gait adaptability tasks including 1) stepping on targets, 2) negotiating obstacles and 3) negotiating obstacles and targets. Gait adaptability tasks reflect the ability to step quickly and appropriately to avoid obstacles and are dependent on neuropsychological, sensorimotor, and balance control. Thus the aim of this study was to investigate underlying neural mechanisms in people with PD while performing such complex tasks. These parallel measurements allow the understanding of the underlying mechanisms of various physical symptoms of PD.

2) Dual Task: In addition to single tasks, there are some studies that examined participants with dual tasks while walking or turning.It has been suggested that during simple tasks, cognitive resources attempt to compensate for motor deficits due to PD, however, under challenging conditions such as dual tasks, overloading occurs [45]. Dual-tasking causes a cognitive challenge since it needs the allocation of more attentional resources. Deficits in executive function due to PD have been linked to difficulties in walking while dual tasking, such as walking and talking or walking while paying attention to the passing traffic. Although there are different types of dual tasks, such as motor dual tasks and cognitive dual tasks, the focus of reviewed studies was on cognitive dual tasks. Mainly focused on finding potential mechanisms underlying dual-task difficulties in PD, Nieuwhof et al. [48] examined three different cognitive tasks. Participants were instructed to walk while counting forward, serially subtracting, and reciting digit spans. In this study, the aim of the experiment was to look at the effect of different cognitive tasks on gait performance in people with PD. This is the only study among the reviewed articles with dual task paradigms in their experiment. Several studies have a dual task along with a single task in their protocol, which is explained in the following paragraph.

3) Single and Dual Task: The last group of studies in our review combined different activities in their motion assessment protocol to examine the motor performance of people with PD during challenging conditions. In this group, all of the experiments existed of single and dual tasks to compare the changes in movement measures. In a study by Orcioli-Silva et al. [49], gait was assessed in two walking conditions of single task and dual task. The cognitive dual task in their experiment consisted of a digit vigilance task, which required participants to walk while listening to random numbers played over a speaker and answer questions at the end of each trial. Ranchet et al. [18] examined the motion and balance of PD participants during walking, standing, and cognitive dual task of subtracting and counting forward. Belluscio et al. [34] measured the turn features of people with PD during a turning-in-place under single and dual-task conditions. The dual-task condition consisted of executing the turning task while pushing a handheld button when the participants heard a two-paired letters sequence. In a similar manner, Vitorio et al. [50], assessed gait and turn measures of participants while executing a walking and turning task along with the cognitive dual task. In another study by Vitorio et al. [51], they assessed PD people while single and dual task turning in place. Maidan et al. [52], [53] measured gait features of PD subjects while walking, walking while negotiating obstacles, and walking while serially subtracting. Stuart et al. [54] assessed PD participants while performing walking and turning tasks and walking while involved in a secondary cognitive task. The aim of their study was to investigate the effect of open and closed-loop tactile cueing on people with PD. The study protocol for motion assessment

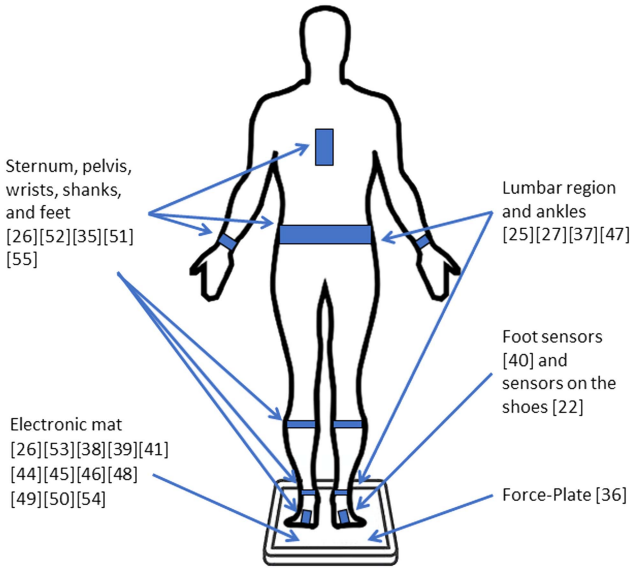

Fig. 2. Sensor placements in the reviewed articles.

in Maidan et al. [23] consisted of usual, single-task walking (comfortable preferred speed) and dual-task walking (serial subtraction of 3 starting from a 3-digit number). Dagan et al. [25] assessed gait features of the participants in a similar manner. Studies considering single and dual-task paradigms for people with PD mainly aim at studying the link between cognition and motor impairments in these people to find the underlying mechanisms of mobility deficits during concurrent tasks.

B. Sensors Used in Movement Assessment

Many studies focused on objective and continuous motion assessment using technology-based devices to examine the disease-related physical symptoms in PD [13]. Two types of motion assessment sensors were found in the literature, wearable motion sensors (n=11), and non-wearable sensors (ground platforms) (n=13). Wearable devices were defined as electronic devices designed to be worn on the body or embedded into watches or clothes. These devices enable the assessment of different outcomes such as postural sway (velocity, frequency, distance), gait (cadence, stride length, stride velocity, gait cycle time), postural transitions (number of steps, duration, step time), and tremor measures [13], [55]. In the studies assessing body motion using wearable devices, sensors were attached or worn on the body in a predefined position and orientation as shown in Fig. 2. Non-wearable devices that have been used for movement assessment in people with PD included electronic walkway and force-plates. An electronic walkway is a portable carpet that contains pressure sensors and can be rolled up for transportation. It is used for laboratory and clinical investigations and provides information regarding several gait parameters, such as walking speed, cadence, and step length [13]. Force-plates can be used to measure postural instability in people with PD. This device has pressure sensors that analyse force distribution and measure center of pressure (CoP) movement during standing tests [13]. Based on the motion and balance task, different sensors were used to assess body motion in people with PD in each reviewed study.

1) Wearable Sensors: Studies that used wearable sensors for the assessment of movements in people with PD have extracted different measures with regard to the performed test. Moreover, based on the location and type of sensors, there are various extracted features in the reviewed articles. For instance, a group of studies performed walking tasks to examine gait features such as gait speed, stride time and length, and cadence using IMUs [18], [23], [25], [36], [39]. In these studies sensors were located on the feet or ankles to measure gait features. The second movement task used in few studies is turning in place. This group of studies extract turning measures such as fluidity of turning, the number of turns, peak speed of the turns, and jerkiness of the turns using IMUs placed on the lumbar region [34], [51]. Overall, IMUs are used in various studies to assess several motion tests and find measures for different body parts.

2) Non-wearable Sensors: The second group of studies used non-wearable sensors to measure body motion of PD participants while performing different tasks. In order to measure gait features, a group of studies used an electronic walkway [24], [35], [37], [38], [43], [44], [45], [47], [48], [49], [52], [53]. In addition, two studies performed standing tests to extract postural sway measures using ground platforms such as a force-plate and electronic walkway [35], [40]. Overall, depending on the protocol of study for movement assessment of people with PD, and also considering the interventions or aim of study, sensors vary in terms of type and location.

C. Regions of Interest

Recording the brain activity of people with PD using fNIRS needs an understanding of different regions in the brain which are related to movements and motor symptoms of PD. Evidence denotes that goal-directed behaviours, such as walking, are always accompanied by automatic processes of postural control involving balance adjustment and muscle activation regulation that rely more on sub-cortical structures [56]. PD impacts sub-cortical circuits leading to dysfunctional automatic movement control. Therefore, walking may rely heavily on compensation from cortical structures in PD [52]. Changes in brain structure and connectivity with PD, impact cognitive processes, walking, and balance [57]. Therefore, impairments of brain activity, motor control, and cognition due to PD potentially mediate task performance. Examining underlying cortical activity involved in walking and balance in PD will allow further clarification of disease-specific links between these features. Different cortical areas have been considered for investigating the activation patterns during various tasks in people with PD. Two main groups for regions of interest were found based on the reviewed studies. Prefrontal Cortex (PFC) was the most commonly studied region (n=21) among the reviewed studies. Only a few studies (n=3) examined the haemodynamic response of the multiple areas such as motor regions (Supplementary Motor Area (SMA), Premotor Cortex (PMC), primary motor cortex (M1)), and the whole Cerebral Cortex. Depending on the special role of each part in the brain, and also the aim of study, different cortical areas

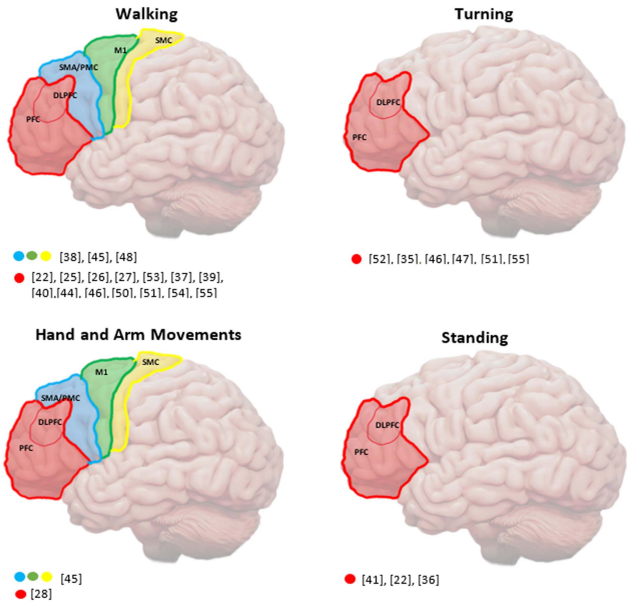

Fig. 3. Summary of activated cortical regions in the reviewed studies while different movement tasks recorded with fNIRS. In this figure, different cortical areas include the prefrontal cortex (PFC), dorsolateral prefrontal cortex (DLPFC), supplementary motor area (SMA), premotor cortex (PMC), and primary motor cortex (M1).

have been considered in the reviewed studies. These areas are summarised in Fig. 3.

1) Prefrontal Cortex (PFC): Since the PFC is involved in human balance and locomotion, it plays an important role in the assessment of the brain activation pattern in patients with PD [58]. Findings from reviewed studies indicate increased activation of the PFC while single-task walking in people with PD compared to the healthy age-matched control group [36], [38]. Several studies considered activation of the PFC while participants performed dual-task walking [23], [24], [25], [43], [48], [49], [52], [53], [53], [54]. Results in these studies showed increased activation of the PFC for people with PD while performing dual tasks compared to healthy age-matched control group. Previous research showed that increased activation in the PFC might be due to deficits in executive function which causes reduced movement automaticity and consequently increased dependence on executive control of movements [52]. Another group of studies examined prefrontal activation of PD people with and without FoG while performing walking and turning tasks [34], [45], [46], [50]. Results of these studies showed that people with PD with FoG had greater PFC activation in different movement conditions compared to patients without FoG. Moreover, two studies that considered activation of the PFC during standing tests [35], [40] found that patients with PD demonstrated significantly higher prefrontal oxygenation levels to maintain postural stability. Abtahi et al. [21] considered PFC activation and features of hand movement tests from people with PD and a healthy age-matched control group to create a model for PD diagnosis.

There are two more studies that have assessed activation patterns in the Dorsolateral Prefrontal Cortex (DLPFC) area [18], [39]. DLPFC is a small part in the PFC and has a known role in the control of executive functions, including inhibitory control [59]. According to Ranchet et al. [18] people with PD had higher DLPFC activity during walking and cognitive dual tasking compared to the age-matched healthy group. In a study by Hoang et al. [39], it was shown that exercise-based training caused a decrease in the cortical activity of the DLPFC in people with PD. Overall, the PFC is the main target of most studies assessing brain activation for people with PD during movement due to its role in motor control.

2) Multiple Cortical Regions: Studies examining activation patterns of multiple cortical regions for people with PD while performing movement tasks, reported various results regarding their aim of research. As suggested by existing research, SMA controls executive planning and motor coordination, and M1 is responsible for motor execution. Additionally, executive planning control and movement initiation are carried out by PMC [60], [61], [62], [63]. All the considered areas relate to the functions that are usually impaired in people with PD. Pelcioni et al. [47] reported greater PMC activation and similar activation in SMA and DLPFC during simple walking for subjects with PD compared to healthy aged-matched controls. Examining activation patterns of cerebral cortex in PD participants during movements, the aim of Jang et al. [37] was to investigate the effect of acupuncture of dorsal side in different cortical areas including PFC, and SMA in this cohort. Klempir et al. [44] also detected changes in motor cortex activity during gait and finger tapping in PD subjects treated with bilateral deep brain stimulation of subthalamic nucleus (DBS-STN). This study examined upper and lower extremities and found that finger tapping (upper limb) resulted in activation of the left side motor and sensorimotor regions. Furthermore, activation values were twice as high during lower limb movements compared to upper limb. Although both of these studies aimed at investigating the effect of applied stimulation on whole cerebral areas, their results show significant activation of areas that are commonly targeted in other studies such as PFC, PMC, SMA, and M1. All of these studies investigated cortical activation in cognitive (DLPFC) and motor (PMC, SMA, M1) cortical regions for people with PD to look at the behaviour of cortical areas other than the PFC.

D. fNIRS Haemoglobin Signals

fNIRS uses optical absorption to monitor heamodynamic responses to brain activation (i.e., changes in oxygenated haemoglobin (HbO_2) and deoxygenated haemoglobin (HHb)) in cortical regions while participants are moving freely [20]. In the reviewed articles, one group of studies considered only HbO_2 concentrations (n= 10). While another group of studies extracted the concentration of HbO_2 and HHb from their fNIRS data (n=14).

1) HbO_2: There is a group of studies that measured only HbO_2 for brain activation recording of people with PD using fNIRS. Results of this group show that HbO_2 is more sensitive to alterations in cerebral blood flow during movement tasks [24], [25], [35], [36], [37], [40], [49], [51], [53], [54]. This group analysed their fNIRS data based on HbO_2 level to investigate the

activation pattern of different cortical regions while participants were performing various gait and balance tests.

2) HbO_2 and HHb: The second group of studies considered both HbO_2 and HHb in their analyses to measure the brain activation of people with PD during movements. Results from these studies show typical cortical activity patterns of increased HbO_2 and stable HHb concentrations during different movement tasks [18], [34], [38], [43], [44], [47], [48], [50]. Among the studies that measured both HbO_2 and HHb, there were several studies that analysed only HbO_2 concentration in their final results [21], [23], [39], [45], [46], [52]. This group of studies considered HbO_2 concentration due to its higher sensitivity and signal-to-noise ratio compared to HHb. According to their results, HHb amount remains stable during cognitive activity. Based on these results, concentration of HbO_2 is more reliable as the outcome of fNIRS in the brain activity assessment of people with PD.

E. Association of fNIRS Data and Motion Outcome Measure

Understanding the relationship between brain activity and body motion gives useful information about the underlying mechanisms of PD and its symptoms. Among the reviewed studies, only 10 articles addressed this relationship. These studies reported the relationship between measures of body motion and brain activity in different ways. We categorised the papers that reported the correlation measure in their study as three groups. Two groups of studies reported the relation between fNIRS outcome and objective motion assessment while walking and turning tasks. One group of studies found no correlation between these two measures. In addition, two studies considered the association of brain activity and body motion measures, however, they did not report their final results. In addition, three studies highlighted the correlation between fNIRS measures and UPDRS III scores that provides valuable insights regarding the underlying neural correlates of motor symptoms in PD.

Those studies that found a correlation between brain activity and body motion measures while participants performed a walking task reported the relations with respect to different gait measures. For instance, results of a study by Orcioli-Silva et al. [24] showed that during unobstructed walking, changes in HbO_2 concentrations are negatively associated with changes in step length variability ($r = -0.468$, $p = 0.028$). While during the obstacle avoidance condition, changes in step time variability are positively associated with changes in the HbO_2 level ($r = 0.481$, $p = 0.026$). Findings of Maidan et al. [52], show that higher cortical activation is related to higher gait speed for people with PD during obstacle negotiation ($r = 0.326$, $p = 0.008$), which is consistent with the findings of Sharon et al. [43]. Vitorio et al. [50] reported that a higher HbO_2 concentration is related to lower FoG severity and lower step time variability during dual-task walking ($r = -0.526$, $p = 0.011$). However, they did not find significant correlations involving PFC activity and FoG severity for people with FoG during single-task walking. In a study by Hoang et al. [39], the brain activity of a group of PD patients following a session of exercise-based training during single-task walking is tested. It has been reported that the right hemisphere HbO_2 changes of this group of participants were negatively correlated with their stride length ($r = -0.588$, $p = 0.035$), whereas there were positive correlations between the left hemisphere HbO_2 changes and their stride length ($r = 0.670$, $p = 0.012$) and stride speed ($r = 0.703$, $p = 0.007$). Overall, the majority of studies considering correlations between fNIRS and motion assessment found a relation between the two measures during simple and dual-task walking. In addition, Jang et al. [37] found a positive correlation between swing ($r = 0.640$, $p = 0.019$) and single support times ($r = 0.652$, $p = 0.016$) with PFC activity while walking during the first to last weeks of intervention application.

On the other hand, some studies reported a correlation between brain activity and body motion during the turning test. For instance, in a study by Maidan et al. [45], they revealed the lower gait speed is associated with higher levels of HbO_2 ($r = -0.441$, $p = 0.002$). In addition, Belluscio et al. [34] found a direct correlation between PFC activation and FoG ratio while turning in people with PD. The FoG ratio is calculated based on shank acceleration signals and is an indicator of FoG severity. In PD people with FoG, Higher PFC activation is associated with a higher FoG Ratio while turning ($r = 0.567$, $p = 0.048$). The few studies considering the relation between brain activation patterns and movement assessments while turning limit the conclusions due to these results.

In addition, two studies found no correlations between brain activation measures and motion assessments. For instance, Stuart and Mancini [54], reported no relationships between body measures and PFC activation during different movement tasks. Similarly, Maidan et al. [23], found no significant correlations among gait performance and PFC measures. These findings are opposed to the previously mentioned results of studies that show direct relations between brain activation and body motion measures.

In the last group, three studies examined the correlation between brain activity and UPDRS III scores to study the neural basis of motor symptoms in PD. Maidan et al. [23], showed there was a mid-significant correlation ($r = 0.142$, $p = 0.050$) between higher MDS-UPDRS III scores, indicating more severe disease, and increased variability in HbO_2 levels specifically during the simple walking task. According to Klempir et al. [44], increased activity of HbO_2 in motor areas during finger tapping coincides with clinical improvement in UPDRS-III score during ON stimulation. In another study by Maidan et al., [52], they found reduced HbO_2 levels during regular walking ($r = -0.280$, $p = 0.022$) and obstacle negotiation walking ($r = -0.355$, $p = 0.003$) were linked to more severe disease symptoms evaluated by UPDRS III scores.

F. Participant's Medication Status

One major difference between the reviewed studies was the medication status of recruited PD participants during experiments. The reviewed studies considered the daily intake of Levodopa among participants with PD. Levodopa is considered as the most effective drug for managing the symptoms of PD [25].

Almost 15 out of 24 papers tested patients ON medication. Moreover, there are four studies considering people with PD while OFF anti-parkinsonian medications (12 hours withdrawal) [34], [44], [50], [54]. In addition, few studies have examined patients in both states of ON and OFF medication [24], [25], [49]. Among the reviewed studies, there are some inconsistent results for ON and OFF medication states during single and dual-task conditions. For instance, Stuart and Mancini [54] did not observe a difference in PFC activity between single and dual-task in people with PD in the OFF medication (levodopa) state. Meanwhile, Dagan et al. [25] showed higher PFC activation in the OFF medication state (levodopa) during dual-task walking compared to single task. Moreover, Orcioli-Silva et al. [49] found increased HbO_2 levels during dual-task compared with single task in the ON medication state (levodopa). Based on the findings of Orcioli-Silva et al. [24], dopaminergic medication (levodopa) may facilitate PFC activation during challenging walking tasks. In general, there are significant differences between the results of studies considering people with PD ON or OFF medication. However, the majority of studies have tested patients ON anti-parkinsonian medications.

These contradictory results during ON and OFF medication during single and dual-task performance of people with PD could have different reasons. In addition to the potential effect of anti-Parkinsonian medications on brain activity and body movements [25], [49], [54], the severity of symptoms while OFF medication is more observable, and the results are more similar to those of advanced PD levels [54]. However, because of the experimental limitations during OFF medication states, in that people with PD will face substantial difficulties in their daily life, the majority of studies considered people with PD while ON medication. These difficulties could limit their participation in studies. To conclude, despite apparent differences in results during different medication statuses, the majority of studies have tested people with PD in the ON state, which is possibly because of the difficulties of people with PD during OFF dopaminergic medications.

IV. Discussion

In this review, we summarised 24 published articles that incorporate objective assessment of brain activity and movement in people with PD using fNIRS and motion sensors (Table IV). In this study, we aimed to answer the research questions outlined in Table II. The summarised data from the reviewed papers included motion and balance tests and sensor types, fNIRS regions of interest and haemoglobin signals, and the relation between brain activity and body motion measures.

RQ1. What are the most common balance and motor task tests for quantitative motion assessment in fNIRS studies in PD?: To answer this question, we reviewed the performed movement assessment tests for people with PD in the literature. We grouped the motion assessment protocol of the reviewed studies into three categories of single tasks, dual tasks, and those with both single and dual tasks. According to our findings, a combination of different single tasks is the mostly used test in the reviewed studies.

The majority of studies used only single tasks in their experiments, including simple walking, complex walking (walking and obstacle avoidance, walking and turning), hand and arm movements, and standing. Among various single motor tasks, studies with complex walking in their experiments were more common. After complex walking tasks, the next common single task in the literature is simple walking. Only a few studies examined participants performing standing or hand movement tests.

Decreased automaticity in patients with PD, results in the recruitment of additional brain networks - specifically cognitive prefrontal areas, even during simple tasks, as a form of compensation. When walking demands exceed prefrontal capacity, under complex walking conditions, like obstacle negotiation, the system may fail and a fall occurs. This highlights the importance of studying PD motor symptoms and their impact on people's life. Different balance and motor tasks in the reviewed studies were designed to extract features that are affected by PD. For instance, studies considering walking tasks in different conditions, are mostly aimed at exploring gait impairments [36], [37], [38], [39]. The main target of the studies which included a turning task was to examine FoG in people with PD [25], [34], [45], [46], [50]. Furthermore, postural instability and any impairment in postural control have been tested by standing tasks [35], [40]. Other symptoms such as tremor have been examined in a few studies with hand movement measurements [21], [44]. Our findings suggest that the aim of the study influences the motor task measured; the aims varied from developing suitable interventions, to diagnosing the disorder or its symptoms, to assessing disease severity.

While one of the reviewed studies considered only dual-tasking, there are studies that combine single and dual tasks in their experiments for more challenging test protocols. It has been shown that in people with PD due to impaired automaticity, more reliance on cognitive resources is needed to maintain performance during activities such as walking [53]. Studies using dual-tasking or challenging walking tests have provided extensive evidence linking gait to cognitive function in PD [25]. Dual-task performance involves the execution of a primary task, such as walking, and a secondary task performed at the same time. During more challenging conditions such as complex walking or dual tasks, allocation of more attentional resources is needed for planning, monitoring and executing a sequence of complex actions. Therefore, studies that consider challenging tests with single and dual cognitive tasks in their experiments, try to find an understanding of the underlying deficits due to PD by investigating motor and cognitive impairments. Results from these studies show that addition of a secondary task negatively affects different features like gait speed, step length, and stride time in people with PD [18], [25], [44], [50]. Studies with the combination of single and dual tasks showed that results could be task-specific. For instance, there are differences between the performance of patients while dual-task walking, dual-task turning, and walking while negotiating obstacles [25], [47], [51]. In general, various aspects in dual tasks such as difficulty level (e.g. size of obstacles), and type of secondary task (motor and cognitive) were considered in the reviewed studies.

RQ2. What motion sensors and metrics are more useful in PD assessment in fNIRS studies?: From the performed literature review, the sensors that are used for objective motion assessment of patients with PD are categorised in two groups: wearable and non-wearable technologies. Taking the limitations of PD participants into consideration, the selection of the appropriate sensor type is of great importance. Our findings show that number of studies that use non-wearable sensors in their experiments are more than those using wearable sensors. The difficulties caused by attaching wearable sensors to older adults especially people with PD, such as inconvenient placement locations, might have been the main reason of the tendency to use non-wearable sensors such as ground platforms. However, due to the difficulty of mobility in people with severe symptoms of PD, performing movement tests in patients' living areas might be safer than asking patients to move to clinics, especially during OFF medication status. This point highlights the importance of the portability of wearable sensors compared to non-wearable ground platforms. Moreover, wearable sensors can measure a wider range of features compared to non-wearable. For instance, in the group of wearable sensors, IMUs are commonly utilised for the assessment of gait during walking tests, turn measures during turning tasks, and hand and arm measures while finger tapping or hand flipping. However, non-wearable devices such as electronic walkway are mostly used for the assessment of gait while walking and in some cases for measuring postural sway during standing tests. Overall, based on the aims and objectives of each study, the advantages and limitations of each sensor should be considered such as size, weight, and sensitivity to artifacts and movements.

In the reviewed studies the extracted motion features are different based on sensor types, sensor locations, and motion assessment tests. Studied metrics in our review include gait features such as speed and time, cadence, and step length; turn measures like turns peak speed and jerkiness; and postural sway measures such as center of pressure. By considering the results of objective motion assessment of PD using wearable and non-wearable sensors, it is clear that gait measures are the most common motion measures among the reviewed studies, regardless of the sensor type. This finding could be linked to the motion assessment protocol and the common motion test between the studies which is walking. To sum up, regardless of sensor types, gait features are the most studied measures of motion in the literature for movement assessment of people with PD. This finding highlights the importance of investigations related to one of the most common limitations of PD which is gait disorders.

RQ3.Which brain areas have been examined in fNIRS studies for people with PD?: Regions of interest (ROI) for examining the cortical activation patterns in the reviewed studies are divided in two main groups of the prefrontal cortex (PFC) and multiple cortical regions, although the PFC was the most commonly investigated region. Among those studies which examined the PFC, two of them recorded the DLPFC activity which is a small part in the PFC, (Fig. 3), and controls the executive functions. The majority of the fNIRS studies examined the PFC, which might be due to the headband nature of the devices not allowing examination of other ROIs. Moreover, many studies have been restricted to the PFC, as there is low hair density in this area, and hair causes poor optical contact [64]. Overall, since the PFC is an easily accessible target through fNIRS [28] and due to its known role in planning, organization, and execution of walking, it has been considered as the main ROI in the literature.

In our review, there were only a few studies considering multiple cortical regions in their recordings of brain activity. In this group, Pelcioni et al. [28] investigated the activation of motor control areas such as SMA, PMC, and M1. Two studies [37], [44] that considered the whole cerebral cortex, found the activated areas (SMA, PMC, M1) were the same as the ROIs in the study by Pelcioni et al. [47]. The neural control of walking and complex tasks such as dual-task walking or obstacle negotiation is mediated by various regions in the brain, among them the frontal lobe. Because of the deficits in executive function caused by PD, patients experience difficulties while performing tasks such as walking or dual tasking. Therefore, investigation of cortical activities related to impaired function caused by PD will help in gaining more understanding of this disorder. In short, selection of ROIs mostly depends on PD-related deficits or it could be task-specific. In other words, depending on the nature of the study, one may consider a special part to investigate changes in brain activation while applying interventions, or while performing a specific movement test.

RQ4.Which fNIRS haemoglobin signals are more useful in studying PD?: After careful consideration of reviewed papers, there were differences in the studies in terms of fNIRS haemoglobin concentrations. Some studies measured HbO_2 and HHb concentrations in their analysis, and another group only considered HbO_2. It was observed that HHb concentration shows no significant changes compared to HbO_2 in studies that have measured both of the parameters but only changes in HbO_2 were found [21], [23], [39], [45], [46], [52]. These findings suggest that HbO_2 concentration could be considered as the main haemoglobin concentration of fNIRS and measurement of HHb would not provide considerable information to the research.

RQ5. What is the most appropriate way to assess the motion and balance measures using sensors and the brain activity measures using fNIRS together?: When considering the brain activity and motion analysis of the body, linking these two measures together will help in understanding their underlying relations. The link between brain activity and body motion has been investigated in different terms such as correlation, fusion, and coherence in the literature [21]. Our findings showed the relationship between brain activity and body movement was one of the most important limitations in the literature as only 10 out of 24 studies addressed this factor.

The relationship between brain activity and body motion has been studied in terms of correlation in some of the reviewed studies. However, there are inconsistencies in the motion measures included in different studies and their results. First, while some studies found no correlations between brain activity and body motion measures [23], [54], other studies have reported positive or negative correlations [24], [34], [37], [39], [43], [45], [50], [52]. Second, studies that have reported the correlation between brain activity and body motion, have considered different motion

measures. This prevents deep understanding of the results as the measured features are not comparable. For instance, in the reviewed studies, Jang et al. [37] and Hoang et al. [39], included the same of walking test in their protocol. While Hoang et al. [39] found the correlation between HbO_2 and stride length and speed, Jang et al. [37] reported the correlation for HbO_2 and two features of swing and single support time. In another example, Sharon et al. [43], reported a correlation between changes of HbO_2 and obstacle avoidance features, such as the amplitude of foot trajectories over the obstacle, while Orcioli-Silva et al. [24], reported a relationship between changes of HbO_2 and gait parameters such as step time variability. Third, some studies reported on the relation between brain activity and behavioural measures, such as number of falls or UPDRS III measure. Since other studies are reporting the relation between brain activity and body motion, behavioural measures could not be considered as a direct correlation factor between brain activity and body movements. Thus interpretation of the results might be difficult for further study. For instance, Maidan et al. [53] did not find a correlation between brain activity and body motion, however, they reported correlation between brain activity and the number of prospective falls in participants. Overall, all these inconsistencies in the literature prevent further understanding of the relationship between brain activity and body motion measures in PD.

Assessing the relationships between brain activity and body motion using measures such as correlation, coherence, and fusion furthers our understanding of brain impairments and physical symptoms caused by PD. However, there is a vital need to use more advanced methods for data analysis such as machine learning (ML) techniques to study larger and varied types of data [65]. For investigating PD, researchers are interested in assessing the severity of symptoms and disease progression, classifying patients for diagnostic and therapeutic purposes. With access to increased volumes and types of data, there is an increasing need to use ML techniques for the purpose of predictions and classifications. ML algorithms are specifically suited for these tasks given their ability to leverage non-linearities and handle large data sets more efficiently, in particular with large numbers of sensors such as fNIRS. For example, neural networks are powerful tools that can be used to uncover complex, non-linear relationships between quantitative (e.g.,gait measures) and qualitative (e.g., medication adherence) data to classify different stages of the disease [66]. Among the reviewed studies, only one study by Abtahi et al. [21], used ML techniques to classify data obtained from brain activity using EEG and fNIRS and also body motion measures recorded by a set of IMUs. Using the classified data they created a model for distinguishing between PD and non-PD people. This study showed the increased accuracy of their model using all of the obtained data from the assessment of brain activity and body movements compared to considering only a single measure. In brief, we believe that there is a vital need for the use of new techniques such as ML for data analysis and classification of large datasets for finding relations between brain activity and body motion.

Contributions of this study: This review focused on summarising the objective brain activity and body motion assessment of patients with PD. For the purpose of this study, we summarised the existing experiments based on the assessment of brain activity using fNIRS and body movements using sensors. The contributions of this study sit in three groups; 1) summarising the most common motion and balance test for people with PD and the type of considered sensors for this aim, 2) finding the commonly tracked target area for recording of brain activation using fNIRS and its optimum haemoglobin signals as concentration of HbO_2, and 3) exploring the relationship between brain activity and body motion analysis which has been widely neglected in the literature. Overall, the contribution of this study would help with the development of more standardised experimental design and data assessment analysis in future studies.

Limitations of this study: Despite its findings, there are some limitations in this study. First, only one data base (Scopus) has been considered which could limit the number of reviewed studies. However, Scopus was used for our searches as it is the largest database of peer-reviewed literature containing abstract and citations. Second, due to some differences in the experimental design of the reviewed studies such as sample sizes, number of fNIRS channels, and various processing methods of data, we limited the considered factors in our summary table (Table IV). However, the mentioned factors are important and should be taken into account. The diversity of final results out of these factors hinders a direct comparison between the studies and generalisability of findings. Thus we did not address the final results of these studies in this review. Third, there was considerable heterogeneity of study protocols in the reviewed studies that were not considered in the present study. As such, variations in baseline conditions (e.g., sitting/standing/unspecified), and duration and amount of trials. Although these factors have an important role in the study protocols, interpretations of the final results are out of scope of this review and we focused only on objective brain activity and body motion assessments of people with PD. In our future work, complementary studies and reviews are required to elucidate the influence of mentioned factors and limitations on the results of brain activity and body motion assessments in people with PD.

Opportunities in the field: Upon careful consideration of the reviewed studies, it is important to note certain limitations that need to be addressed in future research. First, the literature largely focuses on the effect of PD during movements on the prefrontal cortex, while other brain regions involved in motor and cognitive tasks have been largely neglected. Second, most of the studies that were reviewed focused on the activation of various brain regions in relation to lower limb movements, indicating a need for further exploration of the relation between upper limb movements and activation of brain areas. Third, among the reviewed studies, only one study has addressed the most affected side of the body of the patients [49]. Recent studies have illustrated how motor symptom asymmetry in PD impacts both cognitive and motor functions [67]. Hence, future investigations should consider the asymmetry of motor symptoms in PD when assessing brain activity and body motion measures depending on the aim of the study. Fourth, investigating the relation between UPDRS III and fNIRS measures has been neglected in the literature. Understanding this relationship can

provide valuable insight in terms of underlying neural correlates of motor symptoms. Within the 24 reviewed studies, only three have considered this. Therefore, additional research is required to explore the relationship between these two metrics. Fifth, all studies have included participant cohorts with mild to moderate disease, but it is recommended that future studies should also consider participants with more severe symptoms to investigate their brain activation and body motion measures. It will shed light on how the progression of the disease affects brain activation and body motion measures. Finally, for future research using state-of-the-art methods of data classification and analysis such as ML would allow the research community to design models for the objective assessment and diagnosis of Parkinson's disease.

V. Conclusion

This review article summarised existing findings regarding brain activity and body motion assessment in people with Parkinson's disease to find the appropriate setting for the objective assessment/diagnosis of PD. In summary, according to our findings 1) A combination of simple walking tasks is the most common study protocol in the literature. 2) The prefrontal cortex is the most commonly recorded region of interest for investigations of people with PD's brain activity. 3) Our findings show that HbO_2 concentration is a more effective haemoglobin signal for fNIRS compared to HHb. 4) Among various sensor types, IMUs and electronic walkway are more commonly used technologies for motion assessment in people with PD depending on the study design. 5) In this review, we summarised findings about the correlation between brain activity and body motion measures for a better understanding of the underlying mechanisms of PD physical symptoms.

Authors' Contributions

M.S. designed, processed, and carried out the review and drafted the manuscript. M.G. and R.F.R. cross-checked the screening and included articles, and helped in the critical review and drafting of the manuscript. E.P. helped in the review and drafting of the manuscript. All authors read and approved the final manuscript.

References

[1] M. J. Armstrong and M. S. Okun, "Diagnosis and treatment of Parkinson disease: A review," *JAMA*, vol. 323, no. 6, pp. 548–560, 2020.

[2] J. Gratwicke, M. Jahanshahi, and T. Foltynie, "Parkinson's disease dementia: A neural networks perspective," *Brain*, vol. 138, no. 6, pp. 1454–1476, 2015.

[3] J. G. Nutt, B. R. Bloem, N. Giladi, M. Hallett, F. B. Horak, and A. Nieuwboer, "Freezing of gait: Moving forward on a mysterious clinical phenomenon," *Lancet Neurol.*, vol. 10, no. 8, pp. 734–744, 2011.

[4] R. Cilia et al., "Parkinson's disease beyond 20 years," *J. Neurol., Neurosurgery Psychiatry*, vol. 86, no. 8, pp. 849–855, 2015.

[5] V. E. Kelly, A. J. Eusterbrock, and A. Shumway-Cook, "A review of dual-task walking deficits in people with Parkinson's disease: Motor and cognitive contributions, mechanisms, and clinical implications," *Parkinson's Dis.*, vol. 2012, pp. 747–760, 2012.

[6] C. L. Wielinski, C. Erickson-Davis, R. Wichmann, M. Walde-Douglas, and S. A. Parashos, "Falls and injuries resulting from falls among patients with Parkinson's disease and other Parkinsonian syndromes," *Movement Disord.*, vol. 20, no. 4, pp. 410–415, 2005.

[7] G. V. Prateek, I. Skog, M. E. McNeely, R. P. Duncan, G. M. Earhart, and A. Nehorai, "Modeling, detecting, and tracking freezing of gait in Parkinson disease using inertial sensors," *IEEE Trans. Biomed. Eng.*, vol. 65, no. 10, pp. 2152–2161, Oct. 2018.

[8] C. G. Goetz et al., "Movement disorder society-sponsored revision of the unified Parkinson's disease rating scale (MDS-UPDRS): Scale presentation and clinimetric testing results," *Movement Disord.: Official J. Movement Disord. Soc.*, vol. 23, no. 15, pp. 2129–2170, 2008.

[9] C. Ossig et al., "Wearable sensor-based objective assessment of motor symptoms in Parkinson's disease," *J. Neural Transmiss.*, vol. 123, no. 1, pp. 57–64, 2016.

[10] J. A. Stamford, P. N. Schmidt, and K. E. Friedl, "What engineering technology could do for quality of life in Parkinson's disease: A review of current needs and opportunities," *IEEE J. Biomed. Health Inform.*, vol. 19, no. 6, pp. 1862–1872, Nov. 2015.

[11] M. Mancini, P. Carlson-Kuhta, C. Zampieri, J. G. Nutt, L. Chiari, and F. B. Horak, "Postural sway as a marker of progression in Parkinson's disease: A pilot longitudinal study," *Gait Posture*, vol. 36, no. 3, pp. 471–476, 2012.

[12] W. Maetzler, I. Liepelt, and D. Berg, "Progression of Parkinson's disease in the clinical phase: Potential markers," *Lancet Neurol.*, vol. 8, no. 12, pp. 1158–1171, 2009.

[13] C. Godinho et al., "A systematic review of the characteristics and validity of monitoring technologies to assess Parkinson's disease," *J. Neuroengineering Rehabil.*, vol. 13, no. 1, pp. 1–10, 2016.

[14] D. Long et al., "Automatic classification of early Parkinson's disease with multi-modal MR imaging," *PLoS One*, vol. 7, no. 11, 2012, Art. no. e47714.

[15] S. Stuart, R. Vitorio, R. Morris, D. N. Martini, P. C. Fino, and M. Mancini, "Cortical activity during walking and balance tasks in older adults and in people with Parkinson's disease: A structured review," *Maturitas*, vol. 113, pp. 53–72, 2018.

[16] F. Herold, P. Wiegel, F. Scholkmann, A. Thiers, D. Hamacher, and L. Schega, "Functional near-infrared spectroscopy in movement science: A systematic review on cortical activity in postural and walking tasks," *Neurophotonics*, vol. 4, no. 4, 2017, Art. no. 041403.

[17] S. C. Bunce, M. Izzetoglu, K. Izzetoglu, B. Onaral, and K. Pourrezaei, "Functional near-infrared spectroscopy," *IEEE Eng. Med. Biol. Mag.*, vol. 25, no. 4, pp. 54–62, Jul./Aug. 2006.

[18] M. Ranchet et al., "Changes in prefrontal cortical activity during walking and cognitive functions among patients with Parkinson's disease," *Front. Neurol.*, vol. 11, 2020, Art. no. 601686.

[19] R. F. Rojas, X. Huang, and K.-L. Ou, "Toward a functional near-infrared spectroscopy-based monitoring of pain assessment for nonverbal patients," *J. Biomed. Opt.*, vol. 22, no. 10, 2017, Art. no. 106013.

[20] J. C. Menant et al., "A consensus guide to using functional near-infrared spectroscopy in posture and gait research," *Gait Posture*, vol. 82, pp. 254–265, 2020.

[21] M. Abtahi et al., "Merging fNIRS-EEG brain monitoring and body motion capture to distinguish Parkinsons disease," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 6, pp. 1246–1253, Jun. 2020.

[22] W. Zhang et al., "Multimodal data for the detection of freezing of gait in Parkinson's disease," *Sci. Data*, vol. 9, no. 1, 2022, Art. no. 606.

[23] I. Maidan et al., "Neural variability in the prefrontal cortex as a reflection of neural flexibility and stability in patients with Parkinson disease," *Neurology*, vol. 98, no. 8, pp. e839–e847, 2022.

[24] D. Orcioli-Silva et al., "Cortical activity underlying gait improvements achieved with dopaminergic medication during usual walking and obstacle avoidance in Parkinson disease," *Neurorehabilitation Neural Repair*, vol. 35, no. 5, pp. 406–418, 2021.

[25] M. Dagan et al., "Dopaminergic therapy and prefrontal activation during walking in individuals with Parkinson's disease: Does the levodopa overdose hypothesis extend to gait?," *J. Neurol.*, vol. 268, no. 2, pp. 658–668, 2021.

[26] Y. Guo et al., "High-accuracy wearable detection of freezing of gait in Parkinson's disease based on pseudo-multimodal features," *Comput. Biol. Med.*, vol. 146, 2022, Art. no. 105629.

[27] M. Webber and R. F. Rojas, "Human activity recognition with accelerometer and gyroscope: A data fusion approach," *IEEE Sensors J.*, vol. 21, no. 15, pp. 16979–16989, Aug. 2021.

[28] P. H. Pelicioni, M. Tijsma, S. R. Lord, and J. Menant, "Prefrontal cortical activation measured by fNIRS during walking: Effects of age, disease and secondary task," *PeerJ*, vol. 7, 2019, Art. no. e6833.

[29] C. Udina et al., "Functional near-infrared spectroscopy to study cerebral hemodynamics in older adults during cognitive and motor tasks: A review," *Neurocognitive Aging Behav.*, vol. 11, 2020, Art. no. 367.

[30] M. Sun, A. Watson, and G. Zhou, "Wearable computing of freezing of gait in Parkinson's disease: A survey," *Smart Health*, vol. 18, 2020, Art. no. 100143.
[31] J. P. Lin, H. S. Feng, H. Zhai, and X. Shen, "Cerebral hemodynamic responses to the difficulty level of ambulatory tasks in patients with Parkinson's disease: A systematic review and meta-analysis," *Neurorehabilitation Neural Repair*, vol. 35, no. 9, pp. 755–768, 2021.
[32] D. Moher et al., "Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement," *Ann. Intern. Med.*, vol. 151, no. 4, pp. 264–269, 2009.
[33] N. Toosizadeh, J. Mohler, H. Lei, S. Parvaneh, S. Sherman, and B. Najafi, "Motor performance assessment in Parkinson's disease: Association between objective in-clinic, objective in-home, and subjective/semi-objective measures," *PLoS One*, vol. 10, no. 4, 2015, Art. no. e0124763.
[34] V. Belluscio, S. Stuart, E. Bergamini, G. Vannozzi, and M. Mancini, "The association between prefrontal cortex activity and turning behavior in people with and without freezing of gait," *Neuroscience*, vol. 416, pp. 168–176, 2019.
[35] V. S. Beretta et al., "Effect of different intensities of transcranial direct current stimulation on postural response to external perturbation in patients with Parkinson's disease," *Neurorehabilitation Neural Repair*, vol. 34, no. 11, pp. 1009–1019, 2020.
[36] P. C. Thumm et al., "Treadmill walking reduces pre-frontal activation in patients with Parkinson's disease," *Gait Posture*, vol. 62, pp. 384–387, 2018.
[37] J.-H. Jang et al., "Gait disturbance improvement and cerebral cortex rearrangement by acupuncture in Parkinson's disease: A pilot assessor-blinded, randomized, controlled, parallel-group trial," *Neurorehabilitation Neural Repair*, vol. 34, no. 12, pp. 1111–1123, 2020.
[38] N. R. Conceição et al., "Aerobic exercise combined with transcranial direct current stimulation over the prefrontal cortex in Parkinson disease: Effects on cortical activity, gait, and cognition," *Neurorehabilitation Neural Repair*, vol. 35, no. 8, pp. 717–728, 2021.
[39] I. Hoang et al., "An intensive exercise-based training program reduces prefrontal activity during usual walking in patients with Parkinson's disease," *Clin. Parkinsonism Related Disord.*, vol. 6, 2022, Art. no. 100128.
[40] J. R. Mahoney, R. Holtzer, M. Izzetoglu, V. Zemon, J. Verghese, and G. Allali, "The role of prefrontal cortex during postural control in Parkinsonian syndromes a functional near-infrared spectroscopy study," *Brain Res.*, vol. 1633, pp. 126–138, 2016.
[41] M. Ghahramani, D. Stirling, F. Naghdy, G. Naghdy, and J. Potter, "Body postural sway analysis in older people with different fall histories," *Med. Biol. Eng. Comput.*, vol. 57, no. 2, pp. 533–542, 2019.
[42] D. H. Romero and G. E. Stelmach, "Changes in postural control with aging and Parkinson's disease," *IEEE Eng. Med. Biol. Mag.*, vol. 22, no. 2, pp. 27–31, Mar./Apr. 2003.
[43] T. Sharon et al., "Which obstacle attributes place additional demands on higher-level cognitive function in patients with Parkinson's disease?," *Parkinsonism Related Disord.*, vol. 78, pp. 178–183, 2020.
[44] O. Klempir et al., "Reshaping cortical activity with subthalamic stimulation in Parkinson's disease during finger tapping and gait mapped by near infrared spectroscopy," *J. Appl. Biomed.*, vol. 17, pp. 157–166, 2019.
[45] I. Maidan, H. Bernad-Elazari, N. Giladi, J. M. Hausdorff, and A. Mirelman, "When is higher level cognitive control needed for locomotor tasks among patients with Parkinson's disease?," *Brain Topogr.*, vol. 30, no. 4, pp. 531–538, 2017.
[46] I. Maidan, H. Bernad-Elazari, E. Gazit, N. Giladi, J. M. Hausdorff, and A. Mirelman, "Changes in oxygenated hemoglobin link freezing of gait to frontal activation in patients with Parkinson disease: An fNIRS study of transient motor-cognitive failures," *J. Neurol.*, vol. 262, no. 4, pp. 899–908, 2015.
[47] P. Pelicioni, S. Lord, Y. Okubo, and J. Menant, "Cortical activation during gait adaptability in people with Parkinson's disease," *Gait Posture*, vol. 91, pp. 247–253, 2022.
[48] F. Nieuwhof et al., "Measuring prefrontal cortical activity during dual task walking in patients with Parkinson's disease: Feasibility of using a new portable fNIRS device," *Pilot Feasibility Stud.*, vol. 2, no. 1, pp. 1–11, 2016.
[49] D. Orcioli-Silva et al., "Levodopa facilitates prefrontal cortex activation during dual task walking in Parkinson disease," *Neurorehabilitation Neural Repair*, vol. 34, no. 7, pp. 589–599, 2020.
[50] R. Vitorio, S. Stuart, and M. Mancini, "Executive control of walking in people with Parkinson's disease with freezing of gait," *Neurorehabilitation Neural Repair*, vol. 34, no. 12, pp. 1138–1149, 2020.
[51] R. Vitorio, S. Stuart, A. Giritharan, J. Quinn, J. G. Nutt, and M. Mancini, "Changes in prefrontal cortical activity and turning in response to dopaminergic and cholinergic therapy in Parkinson's disease: A randomized cross-over trial," *Parkinsonism Related Disord.*, vol. 86, pp. 10–14, 2021.
[52] I. Maidan et al., "The role of the frontal lobe in complex walking among patients with Parkinson's disease and healthy older adults: An fNIRS study," *Neurorehabilitation Neural Repair*, vol. 30, no. 10, pp. 963–971, 2016.
[53] I. Maidan et al., "Evidence for differential effects of 2 forms of exercise on prefrontal plasticity during walking in Parkinson's disease," *Neurorehabilitation Neural Repair*, vol. 32, no. 3, pp. 200–208, 2018.
[54] S. Stuart and M. Mancini, "Prefrontal cortical activation with open and closed-loop tactile cueing when walking and turning in Parkinson disease: A pilot study," *J. Neurologic Phys. Ther.*, vol. 44, no. 2, pp. 121–131, 2020.
[55] C. F. Pasluosta, H. Gassner, J. Winkler, J. Klucken, and B. M. Eskofier, "An emerging era in the management of Parkinson's disease: Wearable technologies and the Internet of Things," *IEEE J. Biomed. Health Inform.*, vol. 19, no. 6, pp. 1873–1881, Nov. 2015.
[56] K. Takakusaki, "Neurophysiology of gait: From the spinal cord to the frontal lobe," *Movement Disord.*, vol. 28, no. 11, pp. 1483–1491, 2013.
[57] Q. Tian, N. Chastan, W.-N. Bair, S. M. Resnick, L. Ferrucci, and S. A. Studenski, "The brain map of gait variability in aging, cognitive impairment and dementia—A systematic review," *Neurosci. Biobehavioral Rev.*, vol. 74, pp. 149–162, 2017.
[58] D. J. Clark, D. K. Rose, S. A. Ring, and E. C. Porges, "Utilization of central nervous system resources for preparation and performance of complex walking tasks in older adults," *Front. Aging Neurosci.*, vol. 6, 2014, Art. no. 217.
[59] Y. R. Panikratova, R. M. Vlasova, T. V. Akhutina, A. A. Korneev, V. E. Sinitsyn, and E. V. Pechenkova, "Functional connectivity of the dorsolateral prefrontal cortex contributes to different components of executive functions," *Int. J. Psychophysiol.*, vol. 151, pp. 70–79, 2020.
[60] A. Shumway-Cook and M. H. Woollacott, *Motor Control: Translating Research Into Clinical Practice*. Philadelphia, PA, USA: Lippincott Williams & Wilkins, 2007.
[61] P. H. Pelicioni, S. R. Lord, Y. Okubo, D. L. Sturnieks, and J. C. Menant, "People with Parkinson's disease exhibit reduced cognitive and motor cortical activity when undertaking complex stepping tasks requiring inhibitory control," *Neurorehabilitation Neural Repair*, vol. 34, no. 12, pp. 1088–1098, 2020.
[62] S. S. Kantak, J. W. Stinear, E. R. Buch, and L. G. Cohen, "Rewiring the brain: Potential role of the premotor cortex in motor control, learning, and recovery of function following brain injury," *Neurorehabilitation Neural Repair*, vol. 26, no. 3, pp. 282–292, 2012.
[63] C. H. Kasess, C. Windischberger, R. Cunnington, R. Lanzenberger, L. Pezawas, and E. Moser, "The suppressive influence of SMA on m1 in motor imagery revealed by fMRI and dynamic causal modeling," *Neuroimage*, vol. 40, no. 2, pp. 828–837, 2008.
[64] B. Khan et al., "Improving optical contact for functional near-infrared brain spectroscopy and imaging with brush optodes," *Biomed. Opt. Exp.*, vol. 3, no. 5, pp. 878–898, 2012.
[65] R. F. Rojas, X. Huang, and K.-L. Ou, "A machine learning approach for the identification of a biomarker of human pain using fNIRS," *Sci. Rep.*, vol. 9, no. 1, pp. 1–12, 2019.
[66] A. S. Chandrabhatla, I. J. Pomeraniec, and A. Ksendzovsky, "Co-evolution of machine learning and digital technologies to improve monitoring of Parkinson's disease motor symptoms," *NPJ Digit. Med.*, vol. 5, no. 1, pp. 1–18, 2022.
[67] I. Coloman and A. S. Chimagomedova, "The influence of motor asymmetry on cognitive functions in Parkinson's disease," *Zhurnal Nevrologii i Psikhiatrii Imeni SS Korsakova*, vol. 120, no. 10.Vyp. 2, pp. 74–79, 2020.