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TOPICAL REVIEW

A Systematic Review on Functional Near-Infrared Spectroscopy Concurrent With Quantitative Balance Assessment

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ABSTRACT Functional near-infrared spectroscopy (fNIRS) can be used to study activity patterns in different brain cortical areas involved in balance control. This systematic review aims to report on studies in which balance performance has been quantitatively assessed concurrent with fNIRS neuroimaging. Following the PRISMA guidelines, relevant keywords were used for the search through the Scopus and Web of Science databases. Sixty-eight studies met the inclusion criteria and were imported for data extraction. Information on balance assessment protocols, alterations to the balance control loop, brain regions of interest, fNIRS parameters, the relationships found between brain activity and balance performance, and participant cohort types was extracted. The common balance tasks in fNIRS studies were standing and walking. Standing balance control was mainly measured through sway parameters using force platforms. Walking performance was evaluated through gait parameters mostly assessed by floor sensors or inertial sensors. Some of the balance tasks were challenged through sensory manipulation or dual task interference. Brain activity monitoring via fNIRS was mainly utilized to measure oxygenated haemoglobin concentration in frontal cortex. Out of the 68 included articles, 22 studies investigated and found the relationships between activity patterns in different cortical areas and balance measures. In 32 studies, the effects of different factors such as long-term, biological, and psychological conditions on brain activity and balance performance were studied. This study provides a systematic review on fNIRS studies in which quantitative balance assessment is employed to provide a better understanding of neuromotor control of balance.

INDEX TERMS Cerebral haemodynamics, cortical oxygenation, locomotion, neural control, postural control, stability, posturography.

I. INTRODUCTION

Balance refers to the ability to keep the body in equilibrium and to regain balance after the shift of body segments [1]. This ability is integral to the safe performance of most activities of daily living, freedom of movements, personal independence, and maintenance of quality of life [2]. Balance impairment can lead to devastating results such as an increased risk of falling and consequent injuries [3]. Balance disorders may occur at any phase of life [2], which can result from a wide range of factors including musculoskeletal conditions, neurological diseases, ageing, and any age-related neurodegenerative conditions [4], [5], [6]. Assessing and quantifying an individual's balance control is essential for specifying state of balance function and tracking functional changes. Hence, there are different balance assessment methods used worldwide.

Balance assessment can be conducted objectively or subjectively. Objective balance assessment methods, also referred as quantitative balance assessment methods, provide reliable and accurate evaluation. In quantitative balance assessment, balance performance is evaluated when a participant carries out a balance task. Meanwhile, instruments such as force platforms, electronic walkways, and inertial

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sensors are deployed to measure different aspects of balance control. Advanced data analysis can be utilized to improve the reliability and repeatability of the assessment. On that account, quantitative methods have been proposed for their reliable, repeatable, and objective assessment outcomes [7].

Balance control is represented as a closed loop. The position of the human body is perceived by the sensory inputs from the somatosensory, visual, and vestibular systems. The sensory information is sent to the central nervous system consisting of the brain and spinal cord [8], [9]. Here, the information is combined, processed, and a command is signaled to the musculoskeletal system, which will contract and change the body position [9]. Different approaches use alterations to the balance control loop to change the relationships between sensory systems, central nervous system, and musculoskeletal system [8]. These alterations to the balance control loop provide unique opportunities to reveal how sensory, nervous, and motor signals are integrated to control the postural balance [10].

The brain cortical areas play an important role in maintaining balance [11]. Hence, the assessment of cortical activity concurrent with quantitative balance assessment can help with the identification of neuromotor control of balance. Different neuroimaging technologies, such as functional magnetic resonance imaging (fMRI), electroencephalography (EEG), positron-emission-tomography (PET), magnetoencephalography (MEG), and functional near-infrared spectroscopy (fNIRS) have been developed to monitor brain activity. (All the abbreviations used in this paper are shown in Table 1.) Each of these techniques has its own strengths and limitations and may be used in different contexts or applications. Functional MRI is relatively expensive and has a relatively low temporal resolution [12], [13]. To use EEG, it is often required to use gels or saline solutions to improve the signal-to-noise ratio [14], [15]. Use of radioactive tracer substances in PET makes it not suitable for experiments involving repetitive testing [16]. Compared to these neuroimaging techniques, fNIRS offers good spatial and temporal resolution, wireless settings, and a small size [3], [17], [18], [19], [20]. In comparison to MEG, fNIRS has advantages in terms of portability, cost-effectiveness, and ease of use [21], [22]. fNIRS is particularly suitable for balance assessment tests providing real-time information on changes in brain activity related to motor function. Moreover, its portability makes it a convenient option for both research and clinical settings. Brain activity monitoring using fNIRS has been shown to be promising for understanding the contribution of cortical areas in the control of different balance tasks [23], [24], [25].

The fNIRS technique involves projecting near-infrared light through the scalp and skull into the brain, which is then diffusely refracted, and the intensity changes are measured. Neural activation in response to a stimulus results in an increase in blood flow to the activated area, leading to changes in local concentrations of oxygenated haemoglobin (HbO_2), deoxygenated haemoglobin (HHb), or the total haemoglobin [26]. The fNIRS technique utilizes the low tissue absorption of near-infrared light between 650 and 950 nm to detect changes in local concentrations of HbO_2 and HHb during cortical activation [27], respectively. During stimulus presentation, the cortical activation level is compared with a baseline event without any stimulus or with a control stimulus. The change relative to the baseline provides information about the haemodynamic response to brain activation [28]. A schematic presentation of fNIRS is shown in Fig. 1.

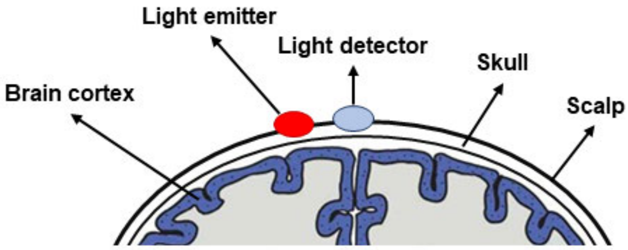

FIGURE 1. A schematic presentation of fNIRS.

According to the important role of fNIRS in understanding the neuromotor control of balance, different reviews have summarized fNIRS studies on balance assessment. However, these reviews have some limitations (Table 2). Some of these studies have included only specific populations such as people with or without neurological disorders, older vs. younger people, and Parkinson's Disease (PD) patients [3], [18], [23], [24], [27], [29], [30]. Some of the reviews have not focused on quantitative balance assessment as an inclusion criterion [2], [3]. Most of these papers have not focused on the relationships between brain activity and balance performance [2], [3], [18], [29], [30]. In some reviews, the focus has been on specific balance tasks such as static, dynamic, and dual tasks [2], [3], [18], [23], [24], [29]. In one study, the brain region of interest (RoI) was limited to the prefrontal cortex (PFC) [24], whereas balance is a whole-brain phenomenon that can be influenced and impacted by nearly every regions of the brain [31]. In addition to these limitations, the rapid growth of research in the field necessitates an updated literature review on fNIRS studies on quantitative balance assessment, which considers different balance tests, alterations to the balance control loop, RoIs, and populations.

This systematic review extends the limited reviews on fNIRS studies that quantitatively assess balance control. It aims to summarize the included studies as follows. First, this paper reports on balance assessment protocols including balance tests, assessment instruments, and measures, in fNIRS studies. Second, alterations to the balance control loop, including dual task interference and sensory manipulation are illustrated. Third, brain RoI and fNIRS settings are reported. Fourth, the relationships found between brain activity and balance performance are presented. Lastly, participant cohort types and their brain abnormalities studied in the reviewed literature are assessed. Fig. 2 details the organization of this paper. This systematic review can lead

TABLE 1. List of abbreviations used in this systematic review.

Abbreviation	Term	Abbreviation	Term	Abbreviation	Term
3D	Three-dimensional	IMU	Inertial measurement units	PS	Parkinson syndrome
AP	Anterio-posterior	IPL	Inferior parietal lobes	PMC	Premotor cortex
BCI	Brain-computer interface	LSOL	Left lower body and stand on one leg	pPCS	Persistent postconcussion symptoms
CAI	Chronic ankle instability	MEG	Magnetoencephalography	RHK	Right heel kick
CG	Control group	ML	Medio-Lateral	RMS	Root mean square
Chan. #	Number of channels	MS	Multiple sclerosis	RO	Research objective
COPD	Chronic obstructive pulmonary disease	MTG	Middle temporal gyrus	RQ	Research question
CoP	Centre of pressure	NA	Non-athletes	RoI	Region of Interest
DLPFC	Dorsolateral prefrontal cortex	NGA	Neurological gait abnormalities	SFG	Superior frontal gyrus
EA	Endurance athletes	NM	Not mentioned	SMA	Supplementary motor area
EEG	Electroencephalogram	PD	Parkinson's Disease	SOT	Sensory organization test
FoG	Freezing of gait	PET	Positron-emission-tomography	SRC	Sport related concussion
fMRI	Functional magnetic resonance imaging	PFC	Prefrontal cortex	SSC	Somatosensory cortex
fNIRS	Functional near-infrared spectroscopy	PostCG	Post central gyrus	VV	Visual vertigo
HbO_2 HHB	Oxygenated haemoglobin Deoxygenated Haemoglobin	PreCG	Precentral gyrus	vs.	Versus

TABLE 2. Summary of other review papers identified in the literature.

Cite Year	Time Span	Included Papers	Aim of Review Paper; those related to the aims of this review	Review Paper Limitations
[2] 2017	-	56	To summarize the knowledge about application and data processing in fNIRS studies dealing with walking or postural tasks.	1) Limited to studies without BCI. 2) Does not include quantitative balance assessment as an inclusion criterion. 3) Findings limited to those published by 2017.
[29] 2021	-	21	To investigate the development of human gait analysis using a hybrid EEG-fNIRS-based BCI system.	1) Limited to studies, in which gait was assessed as the balance assessment measure. 2) Participant cohorts limited to neurological patients.
[18] 2021	2000- 2020	10	To evaluate studies on cortical activation using fNIRS while performing static and dynamic balance tasks, with emphasis on the location of brain areas activated.	1) Limited to those including balance challenges and standing tasks. 2) Participant cohorts limited to those without any neurodegenerative conditions, isolated joint movement, or coordinated body movement. 3) Findings limited to those published by 2020.
[23] 2017	-	12	To provide an overview of fNIRS studies based on examining gait disorders in neurological patients, and assess neurophysiological correlates of walking processes in gait disorders.	1) Limited to studies working on dynamic balance tasks and postural perturbations. 2) Participant cohorts limited to neurological patients. 3) Findings limited to those published by 2017.
[30] 2021	-	10	To explore the neural mechanisms of cerebral haemodynamic responses to the difficulty level of ambulatory tasks in PD patients.	1) Limited to participant cohorts with PD.
[24] 2019	-	35	To summarize the published research regarding PFC activation patterns during simple and complex walking tasks in young adults, older adults, and clinical groups with balance disorders using fNIRS.	1) Balance tasks limited to walking. 2) Limited to participant cohorts including young people, older people, and/or clinical groups with balance disorders. 3) Brain RoI Limited to PFC. 4) Findings limited to those published by 2019.
[3] 2021	-	35	To quantify the changes in cortical activation patterns between different dual tasks and quantify activation differences between different populations.	1) Limited to dual task walking paradigm. 2) Participant cohorts limited to adults with and without neurological disease. 3) Does not include quantitative balance assessment as an inclusion criteria.
[27] 2020	2013- 2018	46	To describe the use of fNIRS to study frontal lobe haemodynamics during cognitive, motor, and dual tasks in older adults.	1) Limited to dual task interference. 2) Participant cohorts limited to older people. 3) Findings limited to those published by 2018.

to a better understanding of approaches used to study the neuromotor control of balance and identify the current gaps in the field. Research questions (RQ) and objectives (RO) in detail can be found in Table 3.

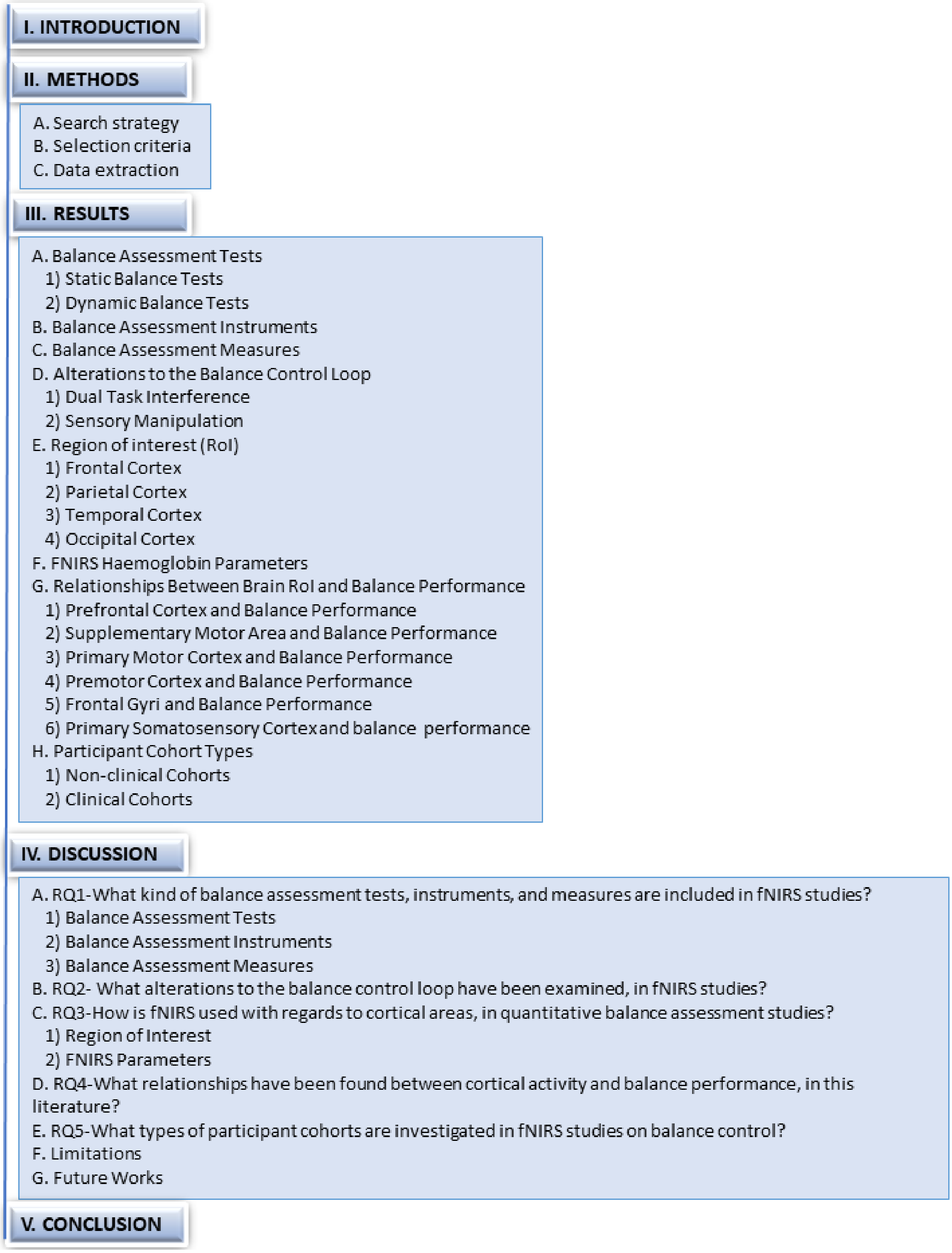

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FIGURE 2. **Organization of contents of this systematic review.**

II. METHODS

A. SEARCH STRATEGY

All available articles addressing quantitative balance assessment and brain cortical activity pattern identification using fNIRS were obtained by searching the Scopus and Web of Science literature databases. Search keywords included three groups combined with "AND," and the terms in each group were linked with "OR" to ensure that at least one term of each group could be found in the results. The first group included *functional near infrared spectroscopy* OR *fnirs* OR *functional*

TABLE 3. Research questions and objectives.

Questions		Objectives	
RQ1	What kind of balance assessment tests, instruments, and measures have been included in fNIRS studies?	RO1	To identify common quantitative balance assessment protocols – including tests, instruments and measures – in fNIRS studies.
RQ2	What alterations to the balance control loop have been examined in fNIRS studies?	RO2	To identify the approaches taken to alter balance control loop in fNIRS studies.
RQ3	How is fNIRS used with regards to cortical areas, in quantitative balance assessment studies?	RO3	To identify the common brain RoI in fNIRS measurement, and frequently used fNIRS parameter (HHb or HbO_2).
RQ4	What relationships have been found between cortical activity and balance performance in the reviewed literature?	RO4	To identify the relationships found between cortical activity pattern and balance assessment measures in the reviewed literature.
RQ5	What types of participant cohorts have been investigated in fNIRS studies on balance tests?	RO5	To recognize which factors in different populations have been investigated in the literature as an influence on balance control and brain activity.

near-infrared spectroscopy OR *cortical oxygenation*. The second group comprised *balance* OR *balance assessment* OR *posture* OR *postural control* OR *postural balance* OR *motion* OR *locomotion* OR *stability* OR *posturography*. The third group included *inertial measurement unit* OR *IMU* OR *force plate* OR *Nintendo* OR *balance board* OR *electronic walkway* OR *gaitrite* OR *camera* OR *pressure sensor* OR *accelerometer* OR *gyroscope* OR *shoe sensor* OR *foot sensor* OR *centre of pressure* OR *sway* OR *stride* OR *gait* OR *body sway*. The database search comprised search terms found in the article title, abstracts, and keywords. Filters were applied to limit the results to the subjects of neuroscience, health professions, psychology, computer science, and engineering, as well as the English language. Moreover, articles from other sources by manual search and reference articles from included studies were imported.

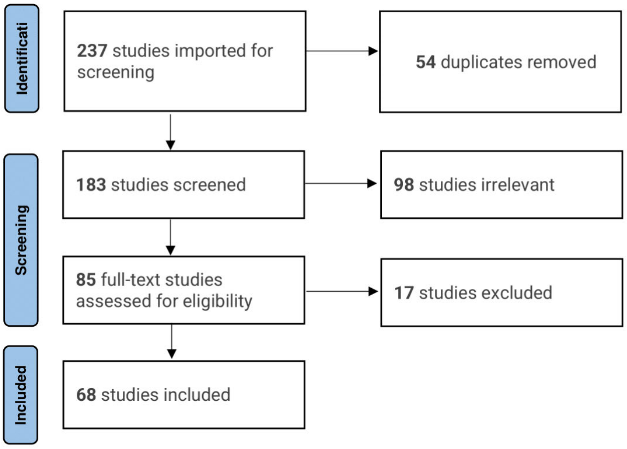

FIGURE 3. PRISMA flow chart of the search strategy.

B. SELECTION CRITERIA

This search was conducted in March 2023. The PRISMA flowchart in Fig. 3 shows the complete selection procedure. In the first phase, the title and abstract were screened to select the articles for full-text reading. Studies having the following exclusion criteria were removed: (1) not broadly relevant to the topic; (2) conducted in children/infants; (3) book sections, review papers, lecture notes, opinion articles, study protocols, and meeting minutes; (4) the only index of muscle activation patterns for balance assessment; (5) assisted walking tasks; and (6) the use of fNIRS for near-infrared spectroscopy-mediated neurofeedback intervention.

In the second phase, the whole paper was read to be included or excluded for data extraction. The exclusion criteria in this phase were as follows: (1) articles in which the balance control was not assessed quantitatively and objectively; (2) studies including an assessment of brain activity before or after the balance test, but not during the test; (3) studies with predefined gait speeds without further assessment during walking; (4) papers not using sensors for balance assessment; (5) articles not mentioning the balance assessment instrument; and (6) those not in line with the review objectives. Studies, which met all of the following criteria, were included in the review: (1) at least one type of balance assessment instrument such as inertial sensors, force platforms, balance board, motion capture system, or electronic walkway was used; and (2) both quantitative balance assessment and fNIRS measurement were simultaneously conducted during each balance test. This selection strategy resulted in a total of 237 articles (54 duplicates). A total of 68 articles matched the inclusion criteria and were examined for data extraction.

C. DATA EXTRACTION

From the included studies, relevant data were extracted and summarized for further analysis, such as: (i) balance assessment protocols including balance assessment tests, instruments, and measures; (ii) alterations to the balance control loop; (iii) brain RoI; (iv) fNIRS parameters; (v) relationships found between RoI and balance performance; and

(vi) participant cohort types and their brain abnormalities. These are described and analysed in more detail next.

III. RESULTS

Regarding the research questions and objectives of this systematic review, the data were extracted from the included papers, and presented in the following order: (a) balance assessment tests: static and dynamic balance tests; (b) balance assessment instruments: wearable and non-wearable instruments employed in static and dynamic balance tests; (c) balance assessment measures: parameters used to quantify and assess balance control; (d) alterations to the balance control loop: approaches used to manipulate the relationships between sensory, nervous, and motor cues, including dual task interference and sensory manipulation; (e) brain RoI: cortical areas investigated through fNIRS; (f) fNIRS parameters: consideration of HbO_2 or\and HHb concentration for cortical activity measurement; (g) relationships found between brain RoI and balance performance: the relationships found between activity of RoIs and balance assessment measures; and (h) participant cohort types: clinical and non-clinical groups of participants studied in the literature and brain abnormalities found in each population. A summary of the results is shown in Table 6, which also includes the number of fNIRS channels and fNIRS wavelengths, in each study. Number of studies in each group of balance assessment instruments, alterations to the balance control loop, fNIRS haemodynamic parameters, and participant cohort types are shown in Fig. 6.

A. BALANCE ASSESSMENT TESTS

Different balance assessment tests have been employed to evaluate individuals' balance performance. Balance comprises of static and dynamic balance. Static balance is the ability to retain the centre of mass above the base of support in a stationary position, whereas dynamic balance is the ability to maintain balance under changing conditions of body movement [32]. In this section, balance tests employed in fNIRS studies to assess balance performance are explained in two groups of static and dynamic balance tests. Summaries of static and dynamic balance assessment protocols, including balance assessment tests, instruments, and measures, used in the reviewed literature are shown in Tables 4 and 5, respectively.

1) STATIC BALANCE TESTS

Twenty-nine out of all 68 articles, included static balance tests, in which participants were asked to stand upright. Since the ability to achieve and maintain equilibrium in an upright stance is an essential and complex lifelong skill [33], a standing test is frequently employed in the literature. In these tests, participants were asked to stand on a fixed ($n = 20$) or\and sway-reference ($n = 9$) support. Tests on a fixed floor varied by feet positions including natural stance [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48] (Fig. 4), one-leg stance [5], [44], [49], Romberg's posture [50], tandem stance [51], and feet together [43], [52], [53].

Different variations of feet position while standing on a fixed support surface affect standing balance [54] and are common in daily life. For instance, one-leg stance is a practical balance test, since it comprises a common part of various activities of daily living such as climbing the stairs, getting on or off the bus, and simple support stances during walking [55] (Fig. 4b). Romberg's posture includes standing with both feet together and hands by the sides [56] (Fig. 4d). In the tandem stance, one foot is behind the other with the big toe of the rear foot touching the heel of the front foot [57] (Fig. 4c). Balance is maintained when the body's centre of gravity is over its base of support [58], and balance control becomes more challenging as the base of support narrows. Hence, standing tests such as standing with feet together, Romberg's posture, tandem stance, and one-leg stance in which the base of support is reduced [43], [49], [57], are more challenging. In general, tests that challenge balance are superior in identifying balance dysfunction to those which measure balance control in optimal or less challenging conditions [59].

In nine studies, participants were asked to stand on a sway-reference support, which is a movable platform that decreases the contribution of the lower limb receptors to control standing [10]. In daily life, there are different instances similar to standing on a sway-reference support such as standing in a bus while it moves [60]. The ability to maintain balance on a sway-reference support was tested in different ways in the literature. For example, in one study, a balance board was mounted on a central ball joint and was free to rotate. In this study, participants were asked to move and keep a tracking ball in the centre of a target zone that was displayed on a computer screen by subtle shifts in body sway [61]. In five studies, individuals tried to maintain the sway-reference support close to horizontal, while it tilted and wobbled [47], [62], [63], [64], [65]. In two more studies, sway-reference support was also used in a semi-immersive virtual reality environment [66], [67]. In one standing test, a temporally unpredictable external perturbation was applied by a support base translation [68]. When balance is perturbed by standing on a movable platform, one must reactively counteract the perturbations through postural movements that either keep the centre of pressure (CoP) within the boundary of the base of support or through reconfiguring the base of support to establish a new stability limit to avoid imbalance [60].

2) DYNAMIC BALANCE TESTS

Thirty-nine studies considered dynamic balance tests including walking ($n = 30$), turning ($n = 1$), walking and turning ($n = 1$), and obstacle course ($n = 7$). The most common dynamic test was walking [6], [69], [70], [71], [72], [73], [74], [75], [76], [77], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96]. Walking is one of the most fundamental motor functions in humans and essential for independent

(a) Natural stance (b) One-leg stance (c) Tandem stance (d) Feet together

FIGURE 4. **Feet positions in different standing tests on a fixed floor.**

mobility [29], [97]. Walking performance is assessed based on different information about the participants' gait parameters, such as gait speed, width, and height [55]. In seven papers, treadmill walking was employed [69], [71], [74], [75], [81], [82], [89], whereas in 21 papers over-ground walking was performed [6], [70], [72], [73], [76], [77], [77], [78], [79], [80], [83], [84], [86], [87], [88], [91], [92], [93], [94], [95], [96]. In two other studies, both treadmill and over-ground walking were performed [85], [90]. The over-ground walking and treadmill walking mechanisms are different. A treadmill imposes a known and constant average velocity; however, in the over-ground walking, participants walk with their own convenient pace [98]. Among the walking tests, four studies considered self-selected walking speed and fast walking speed [70], [75], [87], [89], and two studies considered forward and backward walking [74], [82]. The speed and direction of walking influences musculoskeletal biomechanics, such as joint kinematics, ground reaction forces, joint moments of force and powers, muscle activity, and spatio-temporal gait parameters [99], [100].

Three other dynamic balance tests in the reviewed literature were turning [101], walking and turning [102], and obstacle course [103], [104], [105], [106], [107], [108], [109]. Walking and turning are two frequent and essential daily activities. Turning requires greater centre of mass balance control, compared to linear walking. This can lead to lateral position instability and, hence, falling [97]. In studies that used an obstacle course, different types of obstacle course were studied. An obstacle course demands an individual to perform a set of balance tasks, from basic to fairly challenging, such as obstacle avoidance, or in a specific environment, such as narrow or curvilinear walkways, uneven grounds, or stairs. Such courses may be more useful to estimate daily encounters with environmental challenges [110]. In the reviewed literature, obstacle courses were considered in seven articles. Two studies included walking with and without obstacle avoidance condition [103], [104]. One study included three walking road conditions including wide, narrow, and with obstacles [105]. In a study by Belluscio et al. [106], participants were asked to walk on linear and curvilinear walking paths. In three other studies, individuals were required to step over obstacles on their paths [107], [108], [109]. When an obstacle course is designed based on common environmental challenges, it may represent a better assessment of real life balance control [110].

B. BALANCE ASSESSMENT INSTRUMENTS

Due to the complex nature of balance, numerous instruments were used in the reviewed literature. The devices used for balance evaluation have different resolutions, accuracies, and features, which can influence balance assessment outcomes [111]. These instruments can be non-wearable and wearable motion sensors. In the following paragraphs, the instruments utilized in the included articles are presented. First, instruments used for static balance tests, then, instruments used for dynamic balance assessment, including non-wearable and wearable instruments, are explained. Number of studies using wearable and non-wearable instruments in static and dynamic tests are shown in Fig. 6.

In this literature, two wearable and 27 non-wearable instruments were employed in static tests. Wearable instruments were inertial measurement units (IMUs), attached to participants' lower back [64] and pelvis [65] while they were balancing on a sway-reference support. Among non-wearable instruments, force platforms were used in 21 studies to assess static balance performance. These instruments typically measure ground reaction forces and momentum [112]. There is a wide range of commercial force platforms for static balance assessment including typical force platforms and the Wii Nintendo balance board [113]. A typical force platform is a plate under which there are four distributed dynamo-meters to measure components of force and torque [112]. This instrument was used in 17 studies [5], [34], [35], [36], [40], [41], [43], [45], [46], [47], [48], [49], [52], [53], [63], [67], [68]. The Wii Nintendo balance board resembles a typical force platform, but is relatively inexpensive and highly accessible [113]. Three studies employed the Wii Nintendo Balance Board to assess static postural balance [37], [50], [61]. Another type of force platform used in the literature was the NeuroTest platform in a study by Hoppes et al. [38]. Force platforms are widely used for balance assessment as they provide objective, reliable, and accurate outcomes [112].

In addition to force platform technologies, other non-wearable instruments have been developed to measure static balance parameters. For example, the virtual tilt board [66], balance plate [42], Super Balance [51], 3D inclination sensor [61], pressure sensors (installed on force platforms) [62], reflecting markers [63], electromagnetic tracking system [38], instrumented walkway [39], and pressure distribution measuring device [44] were used in the reviewed literature. Balance assessment instruments vary in terms of different factors such as features, power consumption, price, parameter measurement range, accuracy, and ease of use; and can be chosen based on each study's objectives and aims [114].

Non-wearable and wearable sensors were also used in dynamic balance tests. Twenty-eight studies utilized non-wearable sensors including floor sensors, capacitive pressure sensor matrix, and motion capture system. Floor sensors, in the reviewed literature, include electronic walkways [6], [77], [77], [78], [79], [80], [86], [87], [88], [91], [92], [96], [102], [103] and GAITRite [70], [71], [73], [76], [90], [93], [104], [109]. An electronic walkway is composed of multiple sensor pads connected to form the desired length of the walkway. As participants walk along it, sensors are activated by the pressure of the feet and deactivated when the pressure is released [115]. The GAITRite system is an electronic walkway that automates the collection of spatial and temporal parameters of gait [115]. Walkways and GAITRites are unobtrusive and do not hinder participants' natural walking style.

In this literature, motion capture system, camera, force platform, and capacitive sensors were the other non-wearable instruments employed in dynamic balance tests. A motion capture system typically consists of cameras and sensors that track the position and orientation of markers attached to an individual's body, allowing for the capture of realistic and precise movement data [116]. This system was used in four studies [84], [94], [107], [108]. In one of these studies, motion capture system was coupled with a force platform [94]. In another study by Caliandro et al., [95] a motion capture camera, SMART-D500, was used to measure participants' gait parameters. In one study, force platform was located on treadmill to assess participants' balance control [90]. Capacitive sensors are based on the principle that the condenser capacity changes depending on different parameters, including the distance between the two electrodes [114]. In a study by Beurskens et al. [81], a capacitive pressure sensor matrix was used underneath the walking surface of a treadmill for assessment of gait parameters. Non-wearable sensors are generally non-intrusive; however, they are relatively expensive and are mainly used in laboratory settings [114].

In the reviewed literature, 11 studies used wearable motion sensors to assess dynamic balance control. These sensors include foot switches [82], pressure sensors [74], force sensor [83], and IMUs [69], [72], [75], [85], [89], [101], [105], [106]. Wearable sensor systems have made it possible to obtain different aspects of the human motion in real time by being placed on different parts of the body [114], [117]. Based on the experimental design, examiners are able to decide where to locate the sensors on the body. For example, in a study by Groff et al. [74], participants wore pressure sensors on their feet for calculation of stride time. Similarly, force sensors were located underneath participants' shoes to measure gait parameters in a study by Koren et al. [83]. Inertial measurement units were also located at different places, such as hip [105], knee [105], ankle [85], [105], sternum [72], [101], [106], shins [106], wrists, shanks, feet [72], [101], and lower back [69], [75], [85], [89], [106]. In comparison with non-wearable sensors, wearable sensors may provide cheaper gait analysis systems that can be deployed anywhere [114], [117].

C. BALANCE ASSESSMENT MEASURES

In this section, measures employed in the literature to quantify and assess participants' balance performance are presented. The selection of measures plays an important role in balance assessment, since each measure provides an estimation of a particular aspect of balance control. In the following paragraphs, the measures used in both types of static and dynamic balance assessment are presented.

In most static balance tests, balance performance is measured through body sway in terms of CoP parameters [112]. The CoP is a point corresponding to the projection of the centre of gravity onto the base of support. Postural sway can be quantified using different time- and frequency-based CoP parameters [118]. In the reviewed articles, time-based parameters included sway area [36], [37], [40], [42], [45], [46], [47], [48], [50], [51], [52], [53], sway displacement in the anterio-posterior (AP) [5], [34], [35], [41], [43], [46], [48], [52], [63], [67], [68] and medio-lateral (ML) directions [5], [35], [41], [43], [46], [48], [52], [63], sway path length [36], [38], [44], [45], [46], [47], [48], [51], [53], [63], root mean square (RMS) CoP [38], [49], sway speed [36], [39], [41], [46], [47], [48], [51], and locus length [38]. The only frequency-domain sway feature considered in the literature was sparse density [37], [50]. Sway parameters should be sensitive to small challenges of balance task or changing states of the loco-motor system; however, frequency-based CoP parameters have limited sensitivity [119]. Moreover, such parameters have lower reliability compared with time-based CoP measures [120].

In standing tests on a sway-reference support, other quantities were also considered. For example, in a study by Berreta et al. [68], the recovery time after perturbation was calculated as a static balance assessment measure. It was determined by the time at which CoP variability after perturbation was less than or equal to CoP variability before the perturbation. In two studies, AP translation of centre of mass [64] and pelvis RMS acceleration in ML and AP directions [65] were measured using IMUs. In other tests, the measurement parameters were mainly developed based on the participants' ability to control the support base angle. For example, Lehman et al. [63] measured the displacement of the sway-reference platform while participants were asked to remain as still as possible. In another study, the time that the participants could keep the support base, represented by a ball on the screen, in the target zone was measured [61]. In a study by Hiyamizu et al. [62], the maximal keeping time where one side of the platform did not come into contact with the floor was measured. Ferrari et al. [66] and Moro et al. [67] measured the number of errors. These errors were defined based on how the participants were supposed to keep the support base in a specific angle or at a distance from the floor. Since the principle of standing tests on a sway-reference support is to analyse the reaction to platform movement [121], the displacement of the support base and its related features are studied. These measures can be indicative of an individual's ability to balance on a sway-reference support with different levels of difficulty.

In the reviewed literature, most studies with dynamic tests are focused on some types of walking tests and one study includes only a turning test. Vitorio et al. [101] assessed turning test based on participants' turn peak velocity and duration. Studies with walking tests focused on gait assessment measures. A gait cycle, also known as a stride, is the time period of events during locomotion, in which one heel makes contact with the ground and that same foot makes contact with the ground again. Walking is the result of a series of gait cycles [122]. Different features of gait, including spatial and temporal parameters and their variabilities, are studied in the reviewed literature. Spatial parameters of gait and their variabilities include gait length [70], [71], [72], [73], [76], [80], [81], [82], [84], [86], [89], [90], [96], [102], [103], [104], [105], width [73], [95], length variability [86], [90], [93], [103], [104], [105], and foot strike angle [72]. Temporal parameters of gait and their variabilities include gait speed [6], [70], [71], [72], [73], [76], [77], [78], [79], [80], [84], [85], [86], [87], [88], [90], [91], [92], [93], [94], [96], [102], [103], [104], [105], [106], [107], [108], [109], frequency [106], duration [70], [74], [75], [76], [81], [82], [83], [84], [85], [86], [96], [104], [105], [106], cadence [69], [76], [84], [86], time variability [69], [72], [75], [83], [105], stance time ratio [69], [70], [71], [84], double support time [71], [90], number of steps within 30s [81], [82], and speed variability [105]. Different gait parameters are used to assess walking performance; however, there is no full consensus on which parameters are the most significant to estimate gait performance [117]. Overall, the reviewed literature examines dynamic tests primarily centered on walking and turning, analyzing various spatial and temporal parameters of gait and their variabilities.

D. ALTERATIONS TO THE BALANCE CONTROL LOOP

In this section, we present alterations to the balance control loop implemented in the reviewed literature. These alterations include manipulations to the sensory and central nervous systems. Balance control relies on a closed loop. In this loop, the sensory inputs from somatosensory, visual, and vestibular systems are sent to the central nervous system [8], [10], where they are processed, and a signal is sent to the musculoskeletal system to adjust the body position [10]. Several approaches can be used to change the relationships between sensory systems and central nervous system. These alterations of the balance control loop provide unique opportunities to reveal how sensory, nervous, and motor signals are integrated to control the balance [10], [124]. In the following, alterations to the balance control loop in the included papers are presented. Alterations to the nervous system are conducted through dual task interference, and alterations to the sensory systems are performed through sensory manipulation. Different alterations to the balance control loop during static and dynamic balance tests and the number of studies in each group are shown in Fig. 6.

1) DUAL TASK INTERFERENCE

In the reviewed literature, 33 papers investigated the effect of dual task interference by comparing balance control between dual task and single task performance. Dual task performance refers to the accomplishment of two tasks simultaneously. Everyday life involves numerous situations, in which a balance or motion task is performed concurrently with a secondary task such as standing or walking while talking on the phone. Strong evidence suggests that the central nervous system supports much of the cognitive control of postural balance control [58], [125]. When postural control requires more central processing, cognitive resources may be exceeded by the addition of an attention-demanding task [126]. This may cause interference between the two tasks, displayed in a deteriorated performance in one or both tasks, referred as the dual task cost [126]. In the dual tasks in the reviewed articles, the primary task was walking or standing, while the secondary task was either a cognitive or motor task. The dual tasks considered in the literature are presented in two groups of dual task standing and dual task walking, as follows.

In eight studies, participants' balance performance and brain activity patterns were compared between single task and dual task standing. Brain spectroscopy using fNIRS concurrently with behavioral assessment can provide a better understanding of what is beyond dual task cost [127]. Different cognitive tasks with different levels of difficulty including serial subtraction [35], [42], [43], [52], double-number sequence task [35], [52], reaction task [35], [52], [64], visual and auditory oddball paradigm [40], and spatial and non-spatial working memory tasks [46], [48], [51] were considered. In the double-number sequence task, participants were requested to count the total number of times

TABLE 4. Summary of static balance assessment protocols in the reviewed literature.

Balance test		Balance assessment instrument	Balance assessment measure	
Standing test	Feet position	Non-wearable	Time-based	Frequency-based
On a fixed floor	Natural stance [34]–[48]	• Force platform [34]–[38], [40], [41], [43], [45]–[48] • Electromagnetic tracking system [38] • Balance plate [42] • Instrumented walkway [39] • Pressure distribution measuring device [44]	• Sway area [36], [37], [40], [42], [45]–[48] • Sway displacement in AP direction [34], [35], [41], [43], [46], [48] • Sway displacement in ML direction [35], [41], [43], [46], [48] • Sway path length [36], [38], [44], [45], [47] • Sway speed [36], [39], [41], [46] • RMS sway, locus length [38]	• Sparse density [37]
	One-leg stance [5], [44], [49]	• Force platform [5], [49] • Pressure distribution measuring device [44]	• Sway displacement in AP and ML direction [5] • RMS sway [49] • Sway path length [44]	• Sparse density [50]
	Romberg's posture [50]	• Force platform [50]	• Sway area [50]	
	Tandem stance [51], [53]	• Force platform [53] • Super Balance [51]	• Sway area, sway path length, sway speed [51]	
	Feet together [43], [52]	• Force platform [43], [52]	• sway area [52] • sway displacement in AP and ML direction [43], [52]	

Balance test	Balance assessment instrument		Balance assessment measure	
Standing test	Wearable	Non-wearable	Time-based	Other
On a sway-reference support	IMU [64], [65]	• Force platform [47], [61], [63], [67], [68] • Virtual tilt board [66] • 3D inclination sensor [61] • Pressure sensors [62] • Reflecting markers [63]	• Sway displacement in AP [63], [67], [68] • Sway displacement in ML, sway path length [63]	• Recovery time [68] • Support displacement [63] • Keeping time [61], [62] • Number of errors [66], [67] • AP translation of centre of mass • RMS of pelvis acceleration in ML and AP [65]

two pre-selected digits appeared in a random sequence of three-digit numbers [35], [52]. In the simple reaction time task, participants were asked to respond as fast as possible when hearing an auditory stimulus [35], [52], [64]. In one study, the cognitive tasks included visual and auditory oddball paradigm [40]. The oddball paradigm is usually an active paradigm, which requires an action from the participant, such as pressing the button in response to deviants or counting silently the number of deviants. Altogether, eight studies compared participants' balance performance and brain activity patterns during single and dual task standing, using various cognitive tasks of different difficulty levels.

In 29 studies, participants were asked to perform dual task walking concurrent with dynamic balance task. In dual task walking, dual task costs included the deterioration of gait features such as speed [72], [73], [105], length [72], [73], [105], time, variability [105], and width [73]. In some studies, the second task included pressing a handheld button after a 2-paired letters sequence [72], [101], serial subtraction [73], [75], [76], [86], [92], [96], [103], [105], [106], [108], calculations [107], backward spelling [87], counting forward [96], and visual or verbal-memory demanding tasks [44], [81]. In four studies, the cognitive task was reciting alternate letters of the alphabet which is reciting every other letter of the alphabet in order, starting from a given letter [77], [88], [91], [92]. Two studies included n-back test as the cognitive task [84], [93]. This test consists of a sequence of symbols, and the participants need to indicate if the current symbol is the same as the presented n steps before. In a study by Hawkins et al. [109], the second task was verbal fluency task requiring the participant to say as many words as possible beginning with a randomly selected letter. In another

TABLE 5. Summary of dynamic balance assessment protocols in the reviewed literature.

Balance tests		Balance assessment instrument		Balance assessment measures	
Balance task	Task variation	Non-wearable	Wearable	Spatial	Temporal
Walking	Normal walking [6], [53], [69], [71]–[73], [76]–[81], [83]–[86], [88], [90]–[92], [94]–[96], [123]	• Motion capture system [84], [94] • Walkway [6], [53], [71], [73], [76]–[80], [86], [88], [90]–[92], [96], [123] • Capacitive pressure sensor matrix [81] • Force platform [90], [94] • SMART-D500 [95] • Force sensors [83]	• IMUs [69], [72], [85]	• Gait length [71]–[73], [76], [80], [81], [84], [86], [90], [96] • Gait width [73], [95] • Foot strike angle [72]	• Gait speed [6], [53], [71]–[73], [76], [78]–[80], [85], [86], [88], [90]–[92], [96], [123] • Gait duration [76], [81], [85], [86], [96] • Cadence [69], [76], [84], [86] • Gait time variability [69], [72], [83] • Stance time ratio [69], [71], [84] • Double support time [71], [90] • Number of steps in 30s [81]
	Forward and backward Walking [74], [82]		• Pressure sensors [74] • Foot switches [82]	• Gait length [82]	• Gait duration [74], [82] • Number of steps in 30s [82]
	Self-selected speed and fast walking [70], [75], [87], [89]	• Walkway [70], [87]	• IMUs [75], [89]	• Gait length [70], [89]	• Stance time ratio, gait speed [70] • Gait duration [70], [75], [89] • Gait time variability [75] • Gait velocity [87]
Turning			• IMU [101]		• Turn peak velocity [101] • Turn duration [101]
Walking and turning		• Walkway [102]		• Gait length [102]	• Gait speed [102]
Obstacle course	Obstacle avoidance [103], [104]	• Walkway [103], [104]		• Gait length, gait length variability [103], [104]	• Gait speed [103], [104] • Gait duration [104]
	Wide, narrow, and with obstacle path [105]		• IMUs [105]	• Gait length variability [105]	• Gait speed [105] • Gait duration [105] • Gait time variability [105] • Gait speed variability [105]
	Linear and curvilinear paths [106]		• IMUs [106]		• Gait speed [106] • Gait frequency [106] • Gait duration [106] • Gait frequency [106] • Gait duration [106]
	Upright stands in the path [107], [108]	• Motion capture system [107] • Walkway [108]			• Gait speed [107], [108], [108]

study, participants performed a cognitive task on a smartphone while walking [94]. In one study, the cognitive task was a vigilance task, which required participants to state the number of odd or even numbers they had heard while walking [69]. In four studies, the dual task included walking while talking [6], [78], [79], [80]. In two studies, a motor task including carrying a tray with a bottle of water on the tray was considered [76], [86]. Studies including dual task indicated that the dual task cost varies dependant on the inter-individual differences and the level of the difficulty of the task [73], [75], [76], [78], [79], [80], [103].

2) SENSORY MANIPULATION

Sensory manipulation requires the nervous system to interpret the new sensory conditions and increase reliance on the sensory inputs which have more useful and accurate feedback about balance control [9], [10]. Postural balance mainly relies on the inputs from visual, vestibular, and somatosensory systems. The somatosensory system refers to a group of receptors found throughout the muscles, joints, and skin of the body. Several of these mechano-receptors relay position and motion cues referenced to the body and its different segments, also known as proprioception [128]. All together, muscle and joint receptors encode static and dynamic joint angle and muscle force. Several of the receptors located in the skin of the foot sole act as an interface between the external world and the body. They can sense the contact forces and texture of the support surface that may be used for standing balance [129]. The visual system encodes cues referenced to the external world derived from field of view. From the visual inflow, motion signals of the surrounding world (object-motion) and body within the world (self-motion) are extracted and provide cues to stabilize the upright body [130]. Visual signals also provide cues on the spatial orientation of objects in our surroundings that may be used for controlling posture and responding to disturbances [131]. The vestibular end organs, within the inner ears, sense three dimensional (3D) orientation and inertial cues of the head-in-space [132]. Altogether, cues from these three sensory systems help maintain balance and adjust posture in response to changes in the surroundings.

In the reviewed literature, 12 studies investigated the effect of sensory manipulation by comparing balance test results between different variations of sensory inputs. Alterations to visual, somatosensory, and vestibular inputs were applied through different ways such as changing or removing the visual input, standing on different textures, and standing on a movable platform, respectively. Some studies applied single sensory manipulation, while some other studies applied multiple sensory manipulations. These studies are further explained in the following.

In seven studies, single sensory manipulations were applied during static and dynamic tests. In four of these studies, the influence of the size of the visual field, velocity of the visual target [50], objective flow speed [34], video clip resolution [37], as well as standing with closed eyes [47] were investigated. In one study, the effect of vestibular input on standing balance performance was investigated through different neck and trunk rotation speeds [53]. In two studies, somatosensory manipulation was applied during walking tasks. In one of these studies, participants were asked to wear normal shoes, textured insoles, and no shoes [90]. In the other study, the sensory manipulation was a mismatch between visuospatial perception and lower-extremity proprioception. In this study, a system was used which had four pistons underneath each shoe. During the swing phase of the gait, the pistons could change their length to create a plane oblique to the sole's plane, causing a mismatch between visual prediction and perceived terrain during the stance phase [83].

In five studies, multiple sensory manipulations including visual and somatosensory manipulations ($n = 2$) and visual and vestibular manipulations ($n = 3$) were applied. In a study by Helmich et al. [45], the effect of visual feed back was studied through closed eyes, open eyes, and blurred visual input; and the effect of somatosensory feed back was studied through standing on foam. In a similar study, eyes closed vs. eyes open and standing on a foam vs. solid surface were applied [43]. Helmich et al. [36] investigated the effects of visual and vestibular feed backs by eyes closed vs. eyes opened conditions and stable vs. unstable surface conditions, respectively. In another study, individuals stood in a virtual reality environment and viewed AP optic flow on a fixed or a sway-reference support [38]. These studies provide valuable insights into the nervous system's interpretation of sensory conditions and its reliance on accurate feedback for balance control.

Another multiple sensory manipulation was conducted through The Sensory Organization Test (SOT). This test is a systematic postural test that evaluates balance by altering sensory cues. The SOT allows postural sway to be assessed in six conditions including combinations of movable visual surround, movable support base, and having the participants stand with eyes open or closed [133]. In one study, four conditions of the SOT, including SOT I (fixed floor, eyes open in light), SOT II (fixed floor, eyes open in the dark), SOT IV (sway-reference floor, eyes open in light), and SOT V (sway-reference floor, eyes open in the dark) were applied [41]. The SOT is a systematic and comprehensive postural test that can evaluate balance by altering sensory cues in various conditions.

E. REGION OF INTEREST (RoI)

In this section, brain cortical RoIs studied in the literature are reviewed. Brain cortical areas, located in the cerebral cortex, play an important role in the balance control of daily motor tasks [2]. Four lobes are used to designate specific anatomical locations and functions of the brain including frontal lobe, parietal lobe, temporal lobe, and the occipital lobe [134] (Fig. 5). The study of brain cortical regions and their role in balance control is of great importance as any alteration in the functioning of these structures can lead to altered balance control of an individual [135]. Across all included papers, 52 papers studied activity pattern in the frontal cortex; three papers studied activity in the frontal, temporal, and occipital cortices; nine papers studied the frontal and parietal cortices; two papers studied frontal and temporal cortices; one paper studied the frontal, parietal, and temporal cortices; and one paper studied the temporal and parietal cortices. In one study, temporoparietal region was studied, which is categorized as belonging to the parietal cortex, in this review paper (Fig. 5). In the following, RoIs studied through fNIRS during the performance of balance tasks are presented.

1) FRONTAL CORTEX

In 66 studies, activities of the frontal cortex ($n = 8$) or a frontal cortex sub-region ($n = 58$) were studied. The frontal lobe extends from the back of the forehead to the parietal lobe [134]. This area primarily supports higher-level

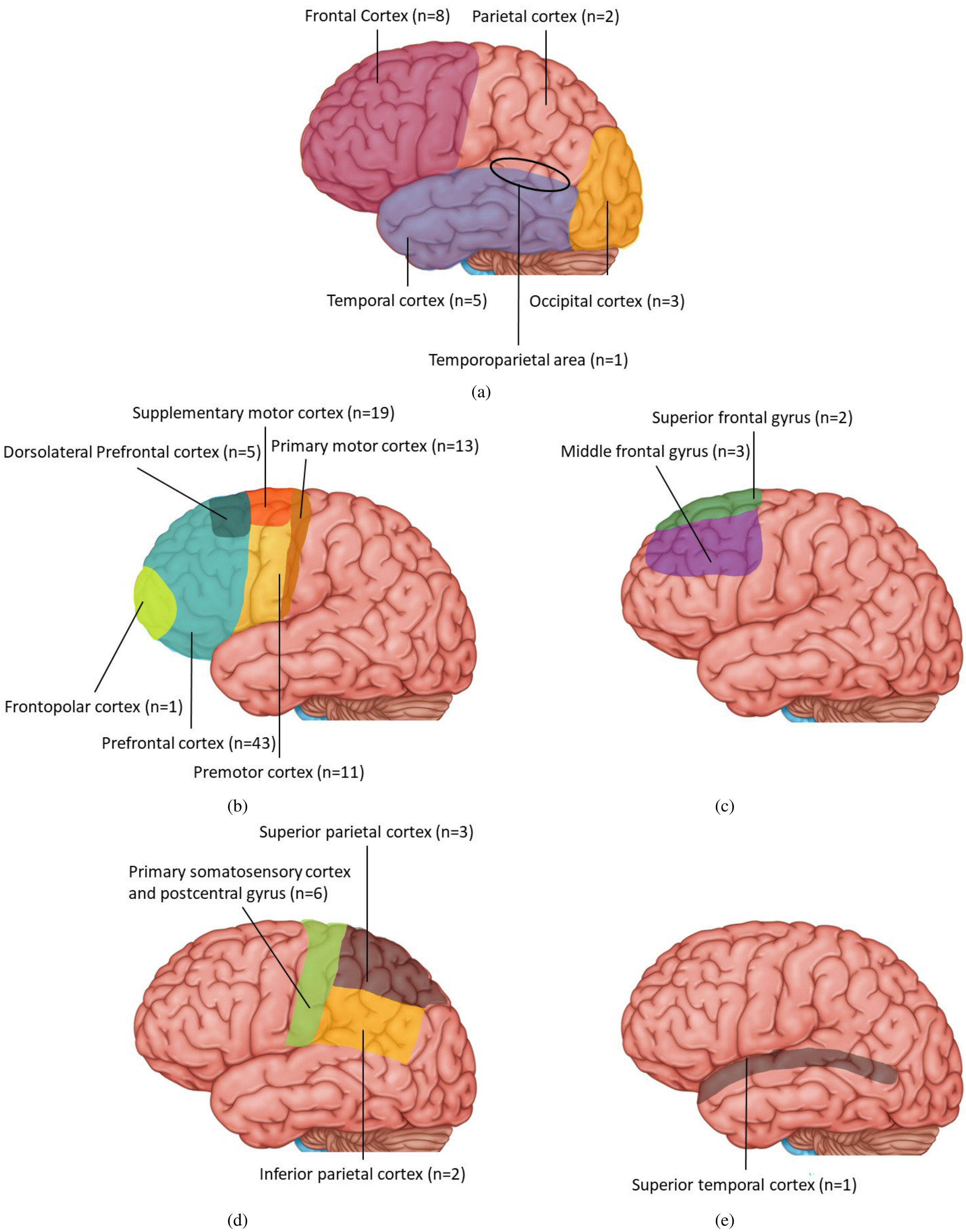

FIGURE 5. Brain regions of interest and the number of reviewed studies (n) focusing on each region. (a) four main brain areas identified in the reviewed studies including frontal, temporal, parietal, and occipital cortex; and temporoparietal area, (b) sub-regions of frontal cortex including prefrontal cortex, frontopolar cortex, premotor cortex, dorsolateral prefrontal cortex, supplementary motor area, and primary motor cortex, (c) other sub-regions of frontal cortex studied in the literature including superior frontal gyrus and middle frontal gyrus, (d) sub-regions of parietal cortex including primary somatosensory cortex and postcentral gyrus, superior parietal cortex, and inferior parietal cortex, and (e) sub-region of temporal cortex, superior temporal cortex.

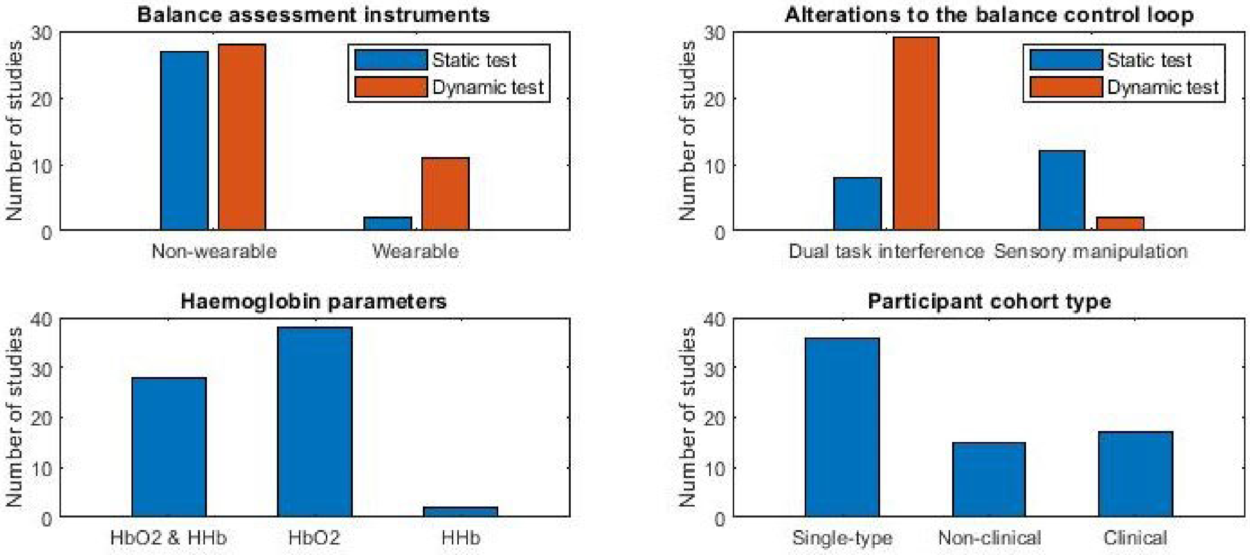

FIGURE 6. Number of studies in each group including: wearable and non-wearable balance assessment instruments in static and dynamic tests; alterations to the balance control loop including dual task interference and sensory manipulation in static and dynamic tests; fNIRS haemoglobin parameters including oxygenated, deoxygenated, and total haemoglobin; and participant cohort types including single-type, non-clinical, and clinical cohorts.

cognitive processes, comprising executive skills and working memory [136], [137]. Executive functions include vital cognitive activities including decision-making, planning, sustained attention, judgment, awareness, and insight [138]. Eight studies investigated frontal cortex activity in the presence of sensory manipulation [37], [41], [45], [50], [53] and dual tasks [40], [51], [96]. The frontal cortex contains different sub-regions among which prefrontal cortex (PFC), premotor cortex (PMC), supplementary motor area (SMA), primary motor cortex, dorsolateral PFC (DLPFC), middle frontal gyrus, and superior frontal gyrus (SFG) are studied in the reviewed literature, details of which are presented in the following. Sub-regions of frontal cortex on the brain are shown in Fig. 5b and Fig. 5c.

The PFC was examined in 43 studies. This area, covering the front of the frontal lobe, plays an important role in cognitive control and the ability to arrange thought and action in accordance with internal goals [139]. The PFC is also a part of the indirect postural pathway; this area is activated when automaticity is reduced, and compensatory executive-attentional resources are required for postural control. Reduction in automacity can rise due to factors such as an individual's lower intrinsic balance ability or challenging perturbations or situations [2], [39], [75]. On that account, in several studies, PFC activity was studied concurrent with dual task performance [6], [35], [42], [43], [46], [48], [52], [69], [72], [73], [75], [76], [77], [77], [78], [79], [80], [84], [86], [88], [91], [92], [93], [94], [103], [105], [106], [107], [108], [109] or in presence of sensory manipulation [66], [67], [68], [83], [90]. In some studies, PFC activity was studied to address prefrontal neural correlates of postural control in PD patients [39], [71], [85], [101], [102]. This area was also investigated during walking with different speeds [70], [89], obstacle avoidance [104], and simple task walking [95].

The DLPFC, a sub-region of PFC, studied in 10 articles, is involved in allocating attentional resources to maintain postural control and integrating external information with information on body position [140]. In one study, this sub-region was studied when participants were performing a one-leg stance [49]. Dorsolateral PFC is involved in executive function and attention. Accordingly, this area was studied concurrent with visual sensory manipulation [34], [47] and dual task performance [44], [64], [84], [87], [103]. Due to the greater activity of DLPFC during the early stages of motor learning [141], this area was studied before and after standing balance learning [62]. Altogether, DLPFC was frequently selected because of its well-established link to executive functioning and balance control [135], [142].

The SMA and primary motor cortex are two RoIs studied in the reviewed literature, which play an important role in motor tasks [143], [144]. The primary motor cortex, located posterior to the precentral sulcus [143], was studied in 13 studies. This area receives and processes inputs from almost all cortical areas implicated in motor control and sends motor commands through the corticospinal tract to modulate postural control [145]. In three studies, the primary motor cortex was studied during dual task walking [75], [104] and before and after motor learning [61]. The SMA, studied in 19 articles, is another important structure in the preparation of foot movement, motor-planning, and movement strategies [146]. In two studies, this area was examined before and after standing balance learning, since it is activated when a previously learned sequence is executed [61], [62]. In four other studies, SMA was studied during dual task walking [44], [69], [76], [86]. Both primary motor cortex and SMA were also studied during one-leg stance [5], [49] and standing on a sway-reference support [65], in the presence of sensory manipulation [47], [63], backward walking [74], [82], walking with different speeds [89], dual task walking [64], [84], and in PD patients [71]. In general, SMA was considered due to its involvement in complexly organized motor tasks and programming voluntary movements with a high degree of complexity [147], and the primary motor cortex was studied in different balance assessment protocols because of its important responsibility in motor control [148].

Two other sub-regions of frontal cortex studied in this literature were the PMC and frontopolar cortex. The PMC, studied in 11 studies [44], [47], [61], [62], [64], [69], [71], [76], [84], [86], [89] is involved in orienting the body and preparing the postural muscles for upcoming movements [149]. The frontopolar cortex occupies the anterior portion of the brain's frontal lobe and is involved in imagination [150]. Accordingly, after closing eyes, the mental activity shifts from an exteroceptive state to an interoceptive state, characterized by imagination and multi-sensory activity depending on information from frontopolar cortices [151]. Hence, in one study, this area was studied with eyes closed vs. eyes opened and fixed vs. sway-reference support conditions [36].

The middle frontal gyrus and SFG are two other frontal sub-regions studied in the included papers. The middle frontal gyrus, studied in three papers, spans from the SFG to the inferior frontal gyrus [38]. According to the reports of middle frontal gyrus abnormalities in clinical vestibular syndromes [152] as well as the important role of the middle frontal gyrus in balance control [153], this area was studied in people with visual vertigo (VV) [38], in presence of sensory manipulation [63] and during dual task walking [81]. The SFG, studied in two articles, is involved in complex movements including several muscle groups [154]. This area was studied during standing on a sway-reference support [63] and through dual task walking [81]. Each RoI can be investigated based on its function in a specific task.

2) PARIETAL CORTEX

The parietal cortex ($n = 2$) and its sub-regions including the primary somatosensory cortex ($n = 6$), superior parietal cortex ($n = 3$), inferior parietal lobe ($n = 2$), and temporoparietal area ($n = 1$) were studied in the reviewed literature (Fig. 5d). The parietal cortex is located posterior to the frontal lobe and superior to the temporal lobe. This area is involved in determining spatial sense, navigation, information integration, and several aspects of the complex motor repertoire [155]. Accordingly, the parietal cortex was studied in the presence of sensory manipulation [41] and during dual task standing [51]. The primary somatosensory cortex (also known as postcentral gyrus) is on the lateral surface of the parietal lobes. This area perceives various somatic sensations from the body, including touch, pressure, temperature, and pain [156]. The primary somatosensory cortex was studied during one-leg stance [5], standing on a sway-reference support [47], [65], and backward walking [74], [82]. In one study, this area was studied in PD patients and healthy controls [71].

The superior parietal cortex, inferior parietal lobe, and temporoparietal area are the other sub-regions of the parietal cortex studied in this review. The superior parietal lobe, bounded in front by the upper part of the postcentral sulcus connected with the postcentral gyrus, plays a key role in sensorimotor integration by actively maintaining an internal representation of one's body [157]. In the reviewed literature, this area was studied through one-leg stance [5], backward walking [82], and standing on a fixed floor [61]. Another sub-region of the parietal cortex included in the reviewed literature was the inferior parietal cortex. This area codes motor acts in a specific way according to the action, in which they are embedded [158]. The inferior parietal lobe was studied during standing on a fixed floor [61] and backward walking [74]. The temporoparietal area, dealing with the integration of visual, somatosensory, and vestibular inputs for balance control [159], was studied for multi-sensory integration in the presence of optic flow stimulation [34]. Overall, different regions of the parietal cortex were investigated with respect to their functions and involvement in the tasks.

3) TEMPORAL CORTEX

In six studies, the activity pattern in the temporal cortex ($n = 5$) or its sub-region, the superior temporal cortex ($n = 1$), were studied (Fig. 5e). The temporal cortex lies posterior to the frontal lobe and inferior to the parietal lobe. In four studies, this area was investigated in the presence of sensory manipulation [37], [41], [50], [53], while in one study this area was investigated through dual task standing [64]. In one paper, the activity pattern of the superior temporal gyrus, which is involved in auditory processing, was studied in the presence of visual and vestibular sensory manipulation [38]. This region spans an area from the inferior frontal gyrus to the middle temporal gyrus [38]. Based on the role of temporal cortex and its sub-regions in sensory input processing, these areas were mainly considered in studies including sensory manipulation.

4) OCCIPITAL CORTEX

The occipital cortex, studied in three papers, is located in the most posterior region of the brain, posterior to the parietal lobe and temporal lobe. In two studies, this area was investigated in the presence of visual input manipulation [37], [50]. The extrastriate cortex processes visual information about body parts, and it lies across the occipito-temporal cortex [160]. This area was studied in patients with VV [38]. Due to the important role of occipital cortex in visual perception, including colour, form, and motion [161], this area was investigated in the presence of visual sensory manipulation.

F. FNIRS HAEMOGLOBIN PARAMETERS

In the included studies, 28 studies used both HbO_2 and HHb concentrations [34], [35], [37], [38], [41], [43], [46], [48], [52], [63], [64], [66], [67], [72], [74], [75], [76], [77], [82], [83], [84], [86], [92], [94], [95], [102], [108], [109], 38 studies used only HbO_2 concentration [5], [6], [36], [39], [40], [44], [45], [47], [49], [50], [51], [53], [62], [65], [68], [69], [70], [71], [73], [77], [78], [79], [80], [81], [85], [87], [88], [89], [90], [91], [93], [96], [101], [103], [104], [105], [106], [107], and two studies used only HHb concentration [42], [61] to describe cortical activation. The number of studies using each of these haemoglobin parameters is also shown in Fig. 6. Using fNIRS, activation can be defined by either an increase in HbO_2 or a decrease in HHb. Oxygenated haemoglobin measures are more expressive of change due to a higher signal-to-noise ratio than HHb [162], [163]. However, HbO_2 has shown to be more vulnerable to systemic contributions such as increased heart rate and respiration, which may not be associated with the task performed [164]. Assessment of both HHb and HbO_2 might correlate closely with the blood-oxygen-level-dependent signal [165].

G. RELATIONSHIPS FOUND BETWEEN BRAIN RoI AND BALANCE PERFORMANCE

In 22 reviewed papers, the relationships between balance assessment measures and activity of PFC, PMC, SMA, primary motor cortex, frontal gyri, and primary somatosensory cortex were investigated and found. Based on the involvement of cortical areas in control of balance [29], these findings are of great importance in better understanding of the neuromotor control of balance. In the following, these relationships are reviewed.

1) PREFRONTAL CORTEX AND BALANCE PERFORMANCE

The relationships between PFC activity and static and dynamic balance performance were studied in four and 12 studies, respectively. In one study, in the presence of sensory manipulations, there were positive correlations between PFC activity and both sway area and sway frequency, in healthy older and younger adults [43]. In another study on different age groups, the prefrontal brain activity was positively correlated with CoP path length [63]. Moro et al. [67] found a positive correlation between returning time, defined as the time required to bring back the centre of mass on the sway-reference board, and the PFC activity. In another study, a positive correlation was found between right DLPFC activation and CoP sway length as well as CoP velocity in AP direction in people with chronic low back pain while they were balancing on a sway-reference support [47]. In the same study, a positive correlation was found between left DLPFC and sway area during natural stance.

In 12 studies, the correlations between PFC activity and gait parameters were studied. Some studies showed that there is a positive correlation between PFC activity and stride duration [106], gait length variability in older adults during obstacle negotiation [103], stride length in dual task walking [80], walking speed during obstacle course [107], and step width [95]. In some other studies, activity in PFC was negatively correlated with walking speed and stride length in dual task walking [73], stride frequency [106], step length variability [89], [104], step velocity variability [89], and gait speed during turning in PD patients [102]. In fast walking, negative correlations were observed between activity in the left PFC and stride length variability [69], step length, step velocity, and swing time [70]. In PD patients, PFC activity was negatively correlated with step time variability during dual task walking [72], and positively correlated with swing time [71]. In a study by Holtzer et al. [6], the association between PFC activity and gait velocity was found to be positive in people with peripheral neurological gait abnormalities (NGA), but negative in those without NGA. In summary, different relationships between brain activity and balance performance were found based on differences in the balance assessment measures, participant cohorts, and balance tests.

2) SUPPLEMENTARY MOTOR AREA AND BALANCE PERFORMANCE

In seven studies, the relationships between SMA and balance assessment measures were found. Negative correlations were noted between activity in SMA and RMS rambling in the ML direction during some of yoga and Tai Chi one-leg stance postures [49], gait performance during dual task walking [86], sway in ML direction [65], and ML sway velocity [47]. In one study in stroke patients, positive correlations were found between lesioned SMA and speed and stride length during waling, walking and cognitive task, and walking and motor task [76]. In these participants, positive correlations were found between non-lesioned SMA and speed during walking and secondary motor task. Kurz et al. [82] reported positive correlations between the amount of variation in the stride-time intervals and the maximum HbO_2 response found in SMA. Positive correlation was also found between right SMA and sway area [47].

3) PRIMARY MOTOR CORTEX AND BALANCE PERFORMANCE

In three papers, the relationships between primary motor cortex activity and balance performance were studied. According to these studies, a positive correlation was found between activity in the primary motor cortex and stride time variability [74], whereas the correlation was negative between primary motor cortex activity and RMS rambling in the ML direction during one-leg stance [49] as well as step length variability and step velocity variability [89].

4) PREMOTOR CORTEX AND BALANCE PERFORMANCE

In four papers, the relationships between PMC and balance performance were studied. In stroke patients, negative correlations were observed between PMC and cadence during both single task and dual task walking [76]. In addition, positive correlations were found between PMC and stride time during walking, walking and cognitive task, and walking and motor task. In this study, a positive correlation was also found between PMC and cadence during walking and motor task [76]. In other studies, negative correlations were found between PMC activity and gait performance during dual task [86], step length variability and step velocity variability [89], and ML sway velocity [47]. Moreover, positive correlation was found between activity in right PMC and sway area [47].

5) FRONTAL GYRI AND BALANCE PERFORMANCE

In two studies, the correlations between frontal gyri and balance performance were studied. The amount of variation in the stride-time intervals while walking was positively correlated with the activity of the pre-central gyrus [82]. Beurskens et al. [81] also reported positive correlation between the activity recorded through one channel on SFG and the number of steps in 30 seconds.

6) PRIMARY SOMATOSENSORY CORTEX AND BALANCE PERFORMANCE

In one study positive correlation was found between left primary somatosensory cortex and sway area during natural stance [47].

H. PARTICIPANT COHORT TYPES

This section presents participant cohorts studied in the reviewed literature. The ability to control balance can change by different factors such as ageing as well as neurological and musculoskeletal disorders [5], [43], [68]. On that account, 32 papers aimed at comparing balance performance and brain activity between different participant cohort types. However, in 36 studies, single type of participant cohort was considered. In the following, multi-type of participant cohorts studied in the literature are categorized into two groups of non-clinical and clinical cohorts. Non-clinical cohorts consist of healthy people such as men vs. women, endurance athletes vs. non-athletes, older adults vs. younger adults, people with different working memory capacities, and older people with and without fear of falling. Clinical cohorts consist of neurological patients, people with musculoskeletal conditions, chronic obstructive pulmonary disease (COPD), and diabetes. The number of studies in each of single-type, clinical, and non-clinical cohorts is shown in Fig. 6.

1) NON-CLINICAL COHORTS

Fifteen studies investigated the effect of age ($n = 10$), fear of falling in older people ($n = 1$), gender ($n = 2$), motor expertise (prior physical activity) ($n = 1$), and working memory capacity ($n = 1$) on balance performance and brain activity. The most frequent cohorts studied among healthy participants were older vs. younger people. In these studies PFC has been found less active in younger participants compared to the older ones [34], [43], [63], [64], [69], [70], [81], [89], [92], [103]. Prefrontal cortex is affected by ageing leading to deficits in executive functions. Higher PFC activation in older adults can be attributed to functional compensation [166]. Fear of falling is defined as an exaggerated concern about falling or as low perceived self efficacy at avoiding falls [167]. In this regard, Holtzer et al. [123] compared the results between older people with and without fear of falling. In this study, they showed that the presence of fear of falling is associated with higher and inefficient PFC activation in older adults. This study interprets that people with fear of falling need to allocate more attentional resources to maintain their balance and reduce the risk of falling. To summarize, the PFC is more active in older individuals compared to younger ones, and fear of falling in older adults is associated with higher and inefficient PFC activation

Gender, long-term physical activity, and memory capacity are the other factors studied among non-clinical cohorts. Gender can cause differences in balance performance and age-related cognitive decline [168]. This effect may be attributed to functional and structural differences in brain regions that are involved in cognitively demanding tasks [80]. Accordingly in two studies, comparisons between older men and women through dual task walking showed higher cortical activity in men than women [78], [80]. Long-term physical activity is shown to be another factor that leads to specific functional and structural brain alterations [169], which are specific to the individual training regime [170]. In this regard, Seidel et al. [61] examined the difference in cortical activity and standing balance between endurance athletes and non-athletes, and observed stronger cortical activity in endurance athletes. Studies reveal that attentional allocation is considered to be a key function of working memory [171], and impaired motor performance is associated with decreased working memory performance [172]. Accordingly, Fujita et al. [44] compared cortical activity and dual task standing performance between groups with low and high spans. In their study, levels of activity were markedly increased in the right DLPFC and SMA in the high-span group during a dual-task. Multi-factorial components contribute to postural balance [173], among which age, fear of falling, gender, motor expertise, and working memory have been investigated among non-clinical cohorts in the reviewed literature.

2) CLINICAL COHORTS

In this section, clinical cohorts studied in the reviewed literature are presented. It has been shown that people with decreased physical function or general health are more likely to have poor balance and an increased risks of falling [174], [175]. For that reason, several studies have been conducted in the reviewed literature to investigate the effects of such factors on balance performance and cortical activity. These factors include neurological disorders, musculoskeletal conditions, chronic obstructive pulmonary disease (COPD), and diabetes which are presented in more detail in the following.

In 14 studies, balance control and cortical activities were compared between neurological patients and control groups.

Various neurological disorders deteriorate specific nervous system functions contributing to balance, leading to an increased risk of falls [176], [177]. Neurological disorders studied in the reviewed literature include concussions ($n = 2$), VV ($n = 1$), NGA ($n = 1$), multiple sclerosis (MS) ($n = 2$), post stroke ($n = 3$), and PD ($n = 5$). Helmich et al. [36] studied symptomatic vs. asymptomatic athletes with sport-related concussions (SRC) causing long-term physical impairments in gait or posture control. In their study, the activity within the left hemispheric frontopolar cortex was significantly reduced in symptomatic athletes compared to asymptomatic athletes. Helmich et al. [45] also compared the results between patients with persistent postconcussion symptoms (pPCS), individuals with a history of mild traumatic brain injury but without pPCS, and healthy controls. Individuals with pPCS had significantly greater activation in frontopolar areas of the right hemisphere.

Visual vertigo and NGA are two other neurological disorders studied in this literature. Visual vertigo is a disease with the symptoms of disorientation and impaired balance induced by conflicting visual and vestibular information or complex visual stimuli in the environment. Individuals with VV may display increased postural sway with full-field visual motion stimuli. Therefore, Hoppes et al. [38] compared individuals with and without VV when viewing optical flow. They observed that the VV group had less increase in the right frontal area in comparison to healthy controls. They concluded that this reduced activation may contribute to the symptoms of VV such as dizziness and disorientation during tasks involving optic flow. Holtzer et al. [6] studied participants with and without NGA through dual task and single task walking. In this study, NGA was defined by the presence of neuropathic gait or gait abnormalities attributed to brain dysfunction. The study showed that the NGA group had reduced activation in the SMA and the precentral gyrus during gait compared to the healthy group.

Another neurological disorder studied in the reviewed literature is MS. Multiple sclerosis is another chronic neurological disease characterized by damage in the central nervous system [178]. Mobility impairments presented as reduced walking performance are a common symptom of MS [178]. Accordingly, Hernandez et al. [79] and Aratanha et al. [84] compared patients with MS and healthy controls during walking. They found higher frontal activity in MS patients and concluded that individuals with MS may require greater neural resources to execute motor tasks.

Stroke is another neurological disorder studied in this reviewed literature. Stroke causes long-term physical disability which can lead to loss of independent locomotion [2]. Hence, Chatterjee et al. [73] recruited adults with chronic post-stroke hemiparesis and subdivided them into low and high balance confidence groups to compare their balance control and brain activity. The group with low balance confidence showed greater prefrontal activity. Hermand et al. [93] also compared low Barthel stroke patients with high Barthel stroke patients, and found lower PFC activity in patients with high Barthel. In another study, a comparison was conducted between post stroke patients with moderate to severe walking deficits, older adults with mild gait deficits, and younger healthy adults [109]. In this study, individuals with walking deficits showed greater PFC activation compared to healthy controls during walking. Altogether, stroke-related mobility deficits require greater neural resources during walking.

Parkinson's Disease is a common disorder among neurological patients. In five studies, cortical activity and balance performance were compared between people with PD [75], [104], or Parkinson's syndrome [39], and healthy control groups; or between subgroups of PD patients [72], [102]. In one study, PFC activity found to be more in PD patients in comparison with healthy adults [39]. In another study, Maidan et al. [102] divided recruited PD patients into two subgroups based on limitations in community ambulation. They observed that patients with relatively better ambulation decreased prefrontal activation compared to patients with relatively worse ambulation. Vitorio et al. [72] recruited PD patients with and without freezing of gait to investigate the influence of freezing of the gait status on the automaticity of walking. They found that PD patients with freezing of gait had greater PFC activation and interpreted that the increase in PFC activity might be a compensatory mechanism to overcome neural deficiencies in PD patients. Moreover, this increase in activity may be associated with greater disease severity.

Musculoskeletal conditions studied in the reviewed literature include chronic ankle instability (CAI) in athletes, chronic low back pain, and chronic gait ataxia. Chronic ankle instability is characterized by repetitive ankle sprains, perceived instability, and feelings of giving way [179]. Rosen et al. [5] considered three groups of individuals with CAI, healthy controls, and coper. Coper was defined as an individual who had sustained an initial ankle sprain, fully recovered, and not developed CAI. In this study, they found no differences in average HbO_2 for any cortical areas. Since postural control deficits are a potential cause of persistent and recurrent pain in patients with chronic low back pain, Li et al. [47] compared patients with chronic low back pain with healthy controls. The results showed that individuals with chronic low back pain had increased activation in the PFC compared to healthy individuals. This increased activation was interpreted as greater cognitive demand and attentional control needed to maintain upright posture in individuals with chronic low back pain. Since ataxia makes gait unstable, Caliandro et al. [95], investigated walking performance and cortical activity between chronic gait ataxia patients and healthy adults. They found increased cortical activity in chronic gait ataxia patients, while there was no activation observed in the healthy participants. According to the reviewed studies, different musculoskeletal conditions can affect cortical activity during balance tasks.

Apart from neurological and musculoskeletal disorders, other clinical conditions such as diabetes ($n = 1$) and COPD ($n = 1$) are investigated in the reviewed literature. Diabetes is another clinical condition that affects balance, which is common in the general population, notably among older adults. The presence of gait alterations has been observed in diabetic patients [180]. Holtzer et al. [77] compared brain activity and gait parameters between diabetic and healthy older adults and found more cortical activity in diabetic patients during walking. Hassan et al. [87] compared COPD patients with healthy controls, and found higher DLPFC activity in patients with COPD. These studies show that diabetes and COPD affect cortical activity in the context of balance control.

IV. DISCUSSION

The aim of this systematic review is to report on fNIRS studies on quantitative balance assessment. A total of 68 studies were reviewed and further illustrated in the Results section and Table 6. In these studies, fNIRS has been used to explore brain cortical activation during different static and dynamic balance assessment tests. In several studies, different approaches including sensory manipulation and dual task interference have been employed to alter the balance control loop. In this paper, the cortical RoIs and haemoglobin parameters studied through fNIRS have been reported. Moreover, the relationships found between fNIRS parameters and balance assessment measures have been presented. Different cohort types of participants including clinical and non-clinical populations were recruited in the reviewed literature. Based on the findings presented in the results, the answers to the research questions are presented and discussed in the following.

A. RQ1-WHAT KIND OF BALANCE ASSESSMENT TESTS, INSTRUMENTS, AND MEASURES ARE INCLUDED IN fNIRS STUDIES?

A variety of balance assessment tests, instruments and measures were employed in the reviewed literature as follows.

1) BALANCE ASSESSMENT TESTS

In the reviewed literature, 29 studies employed static tests and 39 studies employed dynamic tests. All 29 static tests were focused on different standing tests; 20 of which were conducted on a fixed floor and 9 of them were performed on a sway-reference support. Most standing tests on a fixed floor were natural stance, whereas a few of them varied in terms of feet positions. Out of 39 dynamic tests, 30 tests were walking, seven tests included an obstacle course, one test was turning, and one consisted of walking and turning. Out of all walking tests, 21 tests were performed on ground and seven tests were performed on a treadmill. These tests were mainly normal walking while a few varied by backward walking and fast walking tasks. The static and dynamic tests studied in the reviewed literature are further discussed in the following.

Out of 68 reviewed studies, 29 papers included a variety of standing tests indicating the importance of this test in fNIRS studies. This test is practical in use as it takes only 30-60 seconds, does not require specific training, and is not a demanding task. A standing test is used to evaluate an individual's stability, which is indispensable for daily living. The central nervous system, musculoskeletal system and sensory systems are simultaneously involved in controlling one's postural stability. It has been shown that postural stability highly relies on neuronal networks including cortical brain structures [2]. Hence, standing tests in fNIRS studies are used to decode the mechanism through which cortical areas control postural balance.

Most of the included fNIRS studies with standing tests were focused on older people or neurological patients. These studies are of great importance as changes in brain structure caused by ageing or neurological disorder affect the cognitive processes involved in standing [181]. Moreover, in a standing test, fNIRS motion-related and physiology-related artefacts are minimized according to the participant's least head movements and body activities. Head motion might cause changes in light detection and cortical haemodynamic levels, while physiology-related artefacts can cause false haemodynamic responses [182], [183].

In the reviewed literature, most standing tests were conducted on a fixed floor rather than on a sway-reference support. Standing on a sway-reference support can be more challenging, since it involves neural and muscular efforts [184] and demands more functional compensations [185]. Meanwhile, standing on a fixed floor demands less instrumentation and is easier to conduct. In general, standing tests in fNIRS studies are important tests for postural balance assessment and are practical in use.

Among 39 studies including dynamic tests, those having variations of a walking test were the most common. In some studies, obstacle course, walking, and/or turning were considered, in which the motor task is still walking. Walking is one of the most common activities of daily living in which brain cortical areas play an important role. The reviewed studies on walking used fNIRS to record brain activation to investigate neural bases of cognitive contributions in gait and foster a better understanding of the neuromotor control during walking. Some of these studies have introduced a dual task walking, walking tasks that require processing speed and gait adaptability, an obstacle course, or turning to highlight the relative cognitive demand of gait cognitive control. An obstacle course affects the amount of information that must be processed in order to achieve both balance and the motor goal [184]. Turning is another complex walking task that utilizes cognitive resources such as attention, visual spatial function, and executive function [102]. In summary, many fNIRS studies employed more challenging walking tasks to investigate the contribution of cognitive resources to dynamic balance control.

In the reviewed fNIRS studies, similar to standing tests, most of the dynamic tests were taken from older people and neurological patients. In these populations, changes in brain structure lead to changes in gait parameters [181]. Hence,

TABLE 6. Summary of data extracted from the reviewed papers.

Cite	Balance test	Balance assessment instrument/ Measure	Alteration to the balance control loop	Participants (female/male; age [average±SD])	RoI	fNIRS chann#, parameter, wavelength (nm)	(+/-) Relationship RoI AND balance measure-participants and/or task (if applicable)
[52]	Standing	Force Platform/ Sway parameters	Dual task	Healthy older adults (NM; [71.47±6.01])	PFC	NM HbO_2 & HHb 760, 850	—
[50]	Standing	Balance board/ Sway parameters	Visual sensory manipulation	Younger adults (0/13 ; [22.9±1.0]), younger adults (0/11.; [22.6±1.0])	Frontal, temporal, and occipital lobes	48 HbO_2 NM	—
[49]	Standing	Force platform/ Sway parameters	—	Healthy younger adults (20/12; [22±1])	PMC, SMA, DLPFC, primary motor cortex	55 HbO_2 740, 808, 850	(-) Correlation SMA, primary motor cortex AND RMS rambling in ML-RHK. (-) SMA AND RMS rambling in ML-LSOL
[43]	Standing	Force platform/ Sway parameters	Visual, vestibular, and somatosensory sensory manipulation, Dual task	Healthy younger adults (15/9; [20.8±2.4]), healthy older adults (15/10; [70.6±7.1])	PFC	22 HbO_2 & HHb 760, 850	(+) Correlation PFC AND sway area and frequency-all participants
[68]	Standing	Force platform/ Recovery time, sway parameters	—	Idiopathic PD patients (10/14; [68.91±8.47])	PFC	NM HbO_2 760, 850	—
[34]	Standing	Force platform/ Sway parameter	Visual sensory manipulation	Healthy older adults (5/5; [71±5]), healthy younger adults (6/5; [22±1])	DLPFC, left temporoparietal area	64 HbO_2 & HHb 760, 850	—
[35]	Standing	Force platform/ Sway parameter	Dual task	Healthy younger adults (12/6; [21.4±3.96])	PFC	8 HbO_2 & HH 760, 850	—
[36]	Standing	Force platform/ Sway parameters	Visual and vestibular sensory manipulation	Symptomatic athletes with SRC (13/18; [26.9±6.2]), asymptomatic athletes with SRC (9/22; [24.4±4.0])	Frontopolar area	8 HbO_2 760, 830	—
[37]	Standing	Balance board/ Sway parameters	Visual sensory manipulation	Healthy younger adults (NM; [22.6±1.0])	Frontal, temporal and, occipital lobes	48 HbO_2 & HHb NM	—
[5]	Standing	Force platform/ Sway parameters	—	CAI (9/2; [22.2±2.6]), coper group (4/3; [22.0±2.7]), CG (8/5; [22.6±2.3])	SMA, PreCG, PostCG, superior parietal lobe	24 HbO_2 695, 730	—
[38]	Standing	Electromagnetic tracker, Force platform/ Sway parameters	Visual and vestibular sensory manipulation	Adults with VV (10/5; [18-65]), healthy CG (10/5; [18-65])	Middle frontal gyrus, superior temporal gyrus, extrastriate visual area	32 HbO_2 & HHb 830, 690	—
[61]	Standing	Balance board, 3D inclination sensor/ Time of keeping the ball in the zone	—	EA (7/11; [25.06±4.68]), NA (7/8; [25.47±4.23]), CG (5/5; [25.40±4.18])	PMC, SMA, primary motor cortex,SSC, SPL, bilateral IPL	22 HHb 760, 850	—
[103]	Obstacle course	Walkway/ Gait parameters	Dual task	Healthy older adults (10/10; [69.7±5.8]), healthy young adults (13/10; [30.9±3.7])	Anterior PFC, DLPFC	6 HbO_2 760, 850	(+) Correlation PFC AND gait variability-older adults, obstacle negotiation
[105]	Obstacle course	IMU/ Gait parameters	Dual task	Healthy younger adults (12/12; [20–27])	Prefrontal pole area	3 HbO_2 760, 850	—
[6]	Walking	Walkway/ Gait parameters	Dual task	Individuals with central-NGA (20/9; [79.59±7.38]), individuals with peripheral-NGA, (17/23; [77.03±6.27]), normal adults (85/82; [74.43±6.04])	PFC	NM HbO_2 730, 805	Association (-) PFC AND gait velocity-normals, (+) PFC AND gait velocity-peripheral NGA
[39]	Standing	Walkway/ Sway parameters	—	PS patients(15/11; [81.23±5.93]), PD patients (67/50; [77.50±6.72]), CG (69/57; [74.41±6.12])	PFC	NM HbO_2 730, 805	—
[40]	Standing	Force platform/ Sway parameters	Dual task	Healthy adults (3/12; [21– 23])	Frontal cortex	4 HbO_2 NM	—
[62]	Standing	Pressure sensors/ Max time	—	Healthy younger adults (24/15; [21.6±0.8])]	SMA, PMC, DLPFC	50 HbO_2 780, 805, 830	—
[66]	Standing	Virtual tilt board/ Number of errors	—	Healthy adults (0/22; [26.5±4.0])	PFC	8 HbO_2 & HHb NM	—
[41]	Standing	Force platform/ Sway parameters	Visual, vestibular, and somatosensory sensory manipulation	Healthy adults (6/9; [28±9])	Frontal, temporal, and parietal cortex	32 HbO_2& HHb 690, 830	—
[42]	Standing	Balance plate/ Sway parameters	Dual task	Healthy adults (7/13; [22.4±2.1])	PFC	NM HHb 760, 850	—
[63]	Standing	Reflecting markers, force platform/ Platform displacement, sway parameters	Visual and vestibular sensory manipulation	Older adults (18/17; [70.14±4.05]), younger adults (9/18; [24.78±3.48])	SFG, middle frontal gyrus, SMA, PreCG, PostCG, MTG	38 HbO_2 & HHb 760, 850	(+) Correlation PFC AND CoP path length
[69]	Walking	IMUs/ Gait parameters	Dual task	Older adults (12/7; NM), younger adults (20/3; NM)	PFC, primary motor cortex, PMC, SMA	45 HbO_2 780, 805	(-) Correlation left PFC AND stride length variability
[70]	Walking	GAITRite/ Gait parameters	—	Older adults (13/12; [67.37±5.31]), younger adults (12/12; [22.70±1.30])	PFC	8 HbO_2 760, 850	(-) Correlation PFC AND step length, step velocity, swing time-fast walking
[106]	Obstacle course	IMUs/ Gait parameters	Dual task	Healthy younger adults (10/10; [28.4±5.1])	PFC	NM HbO_2 760, 850	(+) Correlation PFC AND stride duration, (-) left PFC AND stride frequency
[104]	Obstacle course	GAITRite/ Gait parameters	—	PD patients (5/18; [70.55±6.03]), CG (15/15; [67.99±5.61])	PFC	3 HbO_2 NM	Correlation (-) PFC AND step length variability-unobstructed walking (+) PFC AND step time variability-obstacle avoidance
[71]	Walking	GAITRite/ Gait parameters	—	PD patients with gait disturbance (3/10; [65.38±7.81]), CG (6/7; [61.46±8.33])	PFC, SMA, primary somatosensory cortex, primary motor cortex, PMC	NM HbO_2 760, 850	(+) Correlation PFC AND swing time
[72]	Walking	IMUs/ Gait parameters	Dual task	PD patients without FoG (5/18; [70.8±7.6]), PD patients with FoG (8/18; [70.3±4.7])	PFC	8 HbO_2 & HHb 760, 850	(-) Correlation PFC AND FoG severity, step time variability-dual task
[73]	Walking	GAITRite/ Gait parameters	Dual task	Adults with chronic post-stroke hemiparesis (11/22; [59.6±9.7])	PFC	NM HbO_2 735, 810	(-) Correlation PFC AND walking speed, stride length-dual task
[74]	Walking	Pressure sensors/ Gait parameters	—	Healthy younger adults (4/6; [22.1±1.4])	SMA, PreCG, PostCG, superior parietal cortex	24 HbO_2 & HHb 695, 830	(+) Correlation primary motor cortex AND stride time variability
[75]	Walking	IMUs/ Gait parameters	Dual task	Healthy older adults (16/6; [59.5±6.8]), PD patients (13/16; [66.3±5.9])	Left PFC, primary motor cortex	NM HbO_2 & HHb 782, 859	—

TABLE 6. ***(Continued.)*** **Summary of data extracted from the reviewed papers.**

[76]	Walking	GAITRite/ Gait parameters	Dual task	Stroke patients (2/21; [51.5±10.7])	PFC, PMC, SMA,	14 HbO_2 & HHb 760, 850	Correlation (+) PMC AND stride time-walking, walking and cognitive task, walking and motor task (+) PMC AND cadence-walking and motor task (+) Lesioned SMA AND speed, stride length-walking, walking and cognitive task, walking and motor task (+) non-lesioned SMA AND speed-walking and motor task
[77]	Walking	Walkway/ Gait parameters	Dual task	Older diabetic patients (19/24; [77.68±6.8]), healthy older people (159/113; [76.71±6.7])	PFC	16 HbO_2 & HHb 730, 805, 850	—
[51]	Standing	Super Balance/ Sway parameters	Dual task	Healthy adults (9/8; [22.47±0.63])	Frontal and parietal cortex	40 HbO_2 780, 830	—
[102]	Walking and turning	Walkway/ Gait parameters	—	High functional PD patients (8/17; [73.5±1.5]), low functional PD patients (8/16; [72.0±1.4])	PFC	6 HbO_2 & HHb 760, 850	(-) Correlation PFC AND gait speed-turning
[78]	Walking	Walkway/ Gait parameters	Dual task	Older adults (179/139; [76.65±6.59])	PFC	NM HbO_2 730, 850	—
[79]	Walking	Walkway/ Gait parameters	Dual task	MS patients (6/2; [57±5]), CG (6/2; [61±4])	PFC	16 HbO_2 730, 805, 850	—
[80]	Walking	Walkway/ Gait parameters	Dual task	Non-demented older adults (205/143; [76.8±6.8])	PFC	16 HbO_2 730, 805, 850	(+) Correlation PFC AND stride length
[67]	Standing	Force platform/ Number of errors	Visual and vestibular sensory manipulation	Healthy adults (0/16; [29.0±4.8])	PFC	8 HbO_2 & HHb NM	(+) Correlation PFC AND returning time-standing on a sway-reference support
[81]	Walking	Capacitive pressure sensor matrix/ Gait parameter	Dual task	older adults (NM ; [71.0±3.8]), younger adults (NM; [24.5±3.3])	Middle frontal gyrus, superior frontal gyrus	14 HbO_2 760, 830	(+) Correlation superior frontal gyrus AND gait performance
[82]	Walking	Footswitch system/ Gait parameter	—	Healthy adults (NM; [23.7±1.4])	SMA, PreCG, PostCG, superior parietal cortex	24 HbO_2 & HHb 695, 830	(+) Correlation PreCG, SMA AND stride time variation
[101]	Turning	IMU/ Turn peak velocity and duration	Dual task	PD patients (6/14; [72.7±7.58])	PFC	8 HbO_2 NM	—
[83]	Walking	Force sensors/ Gait parameters	Sensory manipulation	Healthy adults (11/9; [25.65±1.3])	PFC	6 HbO_2 & HHb 760, 850	—
[107]	Obstacle course	3D motion capture system/ Gait parameter	Dual task	Healthy older adults (36; [65–75])	PFC	22 HbO_2 780, 805, 830	(+) Correlation PFC AND walking speed
[84]	Walking	Motion capture system/ Gait parameters	Dual task	MS patients (20; [35.3±6.3]), healthy CG (19; [35.5±8.0])	PFC, primary motor cortex, SMA, PMC, DLPFC	21 HbO_2 & HHb 780, 805, 830	—
[85]	Walking	IMU/ Gait parameters	—	PD patients (10/10; [69.8±6.5])	PFC	NM HbO_2 NM	—
[86]	Walking	Walkway/ Gait parameter	Dual task	Healthy young adults (8/9; [23.1±1.5])	PFC, SMA, PMC	14 HbO_2 & HHb 760, 850	(-) Correlation PMC, SMA AND gait performance-dual task
[87]	Walking	Walkway/ Gait parameter	Dual task	Patients with COPD (6/9; [70.7±8.0]), CG (11/9; [69.1±6.9])	DLPFC	NM HbO_2 730, 850	—
[44]	standing	Pressure distribution measuring device/ Sway parameter	Dual task	High span group (10/6; [22.5±3.6]), low span group (8/5; [24.0±3.1])	SMA, PMC, DLPFC	42 HbO_2 780, 805, 830	—
[108]	Walking	Motion capture system/ Gait parameter	Dual task	Healthy older adults (13/15; [68.6±4.1])	PFC	22 HbO_2 & HHb 780, 805, 830	—
[64]	Standing	IMU/ Sway parameter	Dual task	Older adults (7/3; [66-81]), younger adults (2/4; [22-30])	Primary motor cortex, SMA, PMC, DLPFC	8 HbO_2 & HHb 690, 830	—
[45]	Standing	Force platform/ Sway parameter	Sensory manipulation	pPCS patients (4/3; [29±15]), adults with a history of mild traumatic brain injury, without pPCS (7/6; [26±7]), healthy CG (6/4; [27±8])	Frontal cortex	16 HbO_2 760, 830	—
[88]	Walking	Walkway/ Gait parameter	Dual task	Older adults (27/28; [74.76±4.97])	PFC	NM HbO_2 730, 805, 850	—
[89]	Walking	IMU/ Gait parameters	—	Younger adults (8/9; [20.3±1.2]), older adults (9/9; [72.6±8.0])	PFC, primary motor cortex, SMA, PMC	40 HbO_2 780, 805, 830	(-) Correlation Frontal cortex AND Step length variability, step velocity variability
[90]	Walking	Force platform, GAITRite/ Gait parameter	Sensory manipulation	Older adults with mild mobility and somatosensory deficits (7/7; [77.1±5.56])	PFC	NM HbO_2 NM	—
[65]	Standing	IMU/ Sway parameters	—	Healthy adults (10; [21–47])	SMA	NM HbO_2 695, 830	(-) Correlation SMA AND sway in ML
[109]	Walking	GAITRite/ Gait parameter	Dual task	Post-stroke with moderate to severe walking deficits (8/16; [58.0±9.3]), older adults with mild gait deficits (8/7; [77.2±5.6]), and young healthy adults (5/4; [22.4±3.21])	PFC	2 HbO_2 & HHb 735, 810	—
[46]	Standing	Force platform/ Sway parameters	Dual task	Younger adults (12/23; [22.91±3.84])	PFC	16 HbO_2 & HHb 730, 850	—
[47]	Standing	Force platform/ Sway parameters	Sensory manipulation	Patients with chronic low back pain (NM; [26.50±2.48]), healthy CG (NM; [25.75±3.57])	Primary motor cortex, SMA, PMC, DLPFC, primary somatosensory cortex	35 HbO_2 730, 850	Correlation (+) right DLPFC AND CoP length, AP velocity-CLBP, sway-reference support, (-) left PMC/SMA AND ML velocity-CG, natural stance, (+) left DLPFC, right PMC/SMA, left primary somatosensory cortex AND sway area-natural stance
[91]	Walking	Walkway/ Gait parameter	Dual task	Older participants (41/42 ;[78.05±6.37])	PFC	16 HbO_2 730, 805, 850	—
[123]	Walking	Walkway/ Gait parameter	Dual task	Older adults with fear of falling (13/6; [79.84±6.01]), Older adults without fear of falling (25/31; [76.73±6.39])	PFC	NM HbO_2 730, 805, 850	—

TABLE 6. ***(Continued.)*** **Summary of data extracted from the reviewed papers.**

[92]	Walking	Walkway/ Gait parameter	Dual task	Younger adults (16/10; [20.9±NM]) Older (16/10;[70.3±NM])	PFC	22 HbO_2 & HHb 760, 850	—
[48]	Standing	Force platform/ Sway parameters	Dual task	Younger adults (12/22; [22.91±3.90])	PFC	NM HbO_2 & HHb 730, 850	—
[53]	standing	Force platform/ Sway parameters	Sensory manipulation	Healthy adults (NM;[25.8±2.1])	Frontal cortex	51 HbO_2 NM	—
[93]	Walking	GAITRite/ Gait parameters	Dual task	Low Barthel stroke patients (4/4; [70.6±10.5]), high Barthel stroke patients (3/10;[66.6±10.4])	PFC	NM HbO_2 NM	—
[94]	Walking	Motion capture system, force platform/ Gait parameters	Dual task	Younger adults (NM;[24.11±4.11])	PFC	16 HbO_2 & HHb 730, 850	—
[95]	Walking	SMART-D500/ Gait parameters	—	Chronic gait ataxia patients (10/9; [31-70]), healthy adults (8/7; [36–73])	PFC	2 HbO_2 & HHb 775, 810, 850	(+) Correlation PFC AND step width
[96]	Walking and standing	Walkway/ Gait parameters	Dual task	Younger adults (13/10; [30.9±3.7])	Frontal cortex	6 HbO_2 760, 850	—

examining the cortical activity involved in gait performance may allow further clarification of links between cortical structure and walking performance. Among the included dynamic tests, most walking tasks were over-ground walking rather than treadmill walking. Walking on a treadmill needs less space, and installing floor sensors on treadmill provides a longer range of gait assessment by non-wearable sensors. However, it affects the biomechanics of walking and demands access to a treadmill. In conclusion, different walking tests are the most common dynamic tests in fNIRS studies, which have the potential to provide a good understanding of neuromotor control in different populations.

2) BALANCE ASSESSMENT INSTRUMENTS

In the reviewed literature, 13 wearable and 55 non-wearable instruments were employed to assess participants' balance control. In static tests, non-wearable instruments were mainly used among which force platforms were most common. In dynamic tests, 28 papers used non-wearable instruments, while 11 studies used wearable instruments. Non-wearable sensors mainly included walkways, whereas most wearable sensors were inertial sensors. Wearable and non-wearable balance assessment instruments are discussed in the following paragraphs, respectively.

Most assessment devices in the reviewed literature were non-wearable instruments. These sensors are more expensive than the non-wearable ones, whereas their common use might be justified in two ways. First, the non-intrusiveness of these instruments might have led to their common application, more specifically for participants with balance impairment. Second, as shown in the reviewed articles, dual task is common in fNIRS studies on balance performance. Non-wearable instruments do not interfere with the attention of the participants on the second task; however, extra sensations from the attached wearable sensors might distract them.

Among non-wearable instruments, force platforms and floor sensors were most commonly used for standing and walking tests, respectively. A force platform is utilized for sway measurement and is considered as the gold standard in the field [110], whereas a walkway is mainly used for gait assessment. These instruments are portable, whereas they require a significant amount of space [114]. On walkways, participants can walk only for 4 to 5 steps, so to overcome this problem, an electronic walkway can be installed on a treadmill [71]. However, the biomechanics of over-ground walking are different from those of treadmill walking, which might affect gait parameters [98]. Although non-wearable sensors are more expensive than wearable sensors, their non-intrusiveness might have led to their widespread use in the literature [114].

In 11 studies including dynamic tests, wearable sensors, mainly inertial sensors, were employed to assess gait measures. The usage of these sensors in dynamic balance tests can be explained in different ways. These sensors are useful in challenging walking tasks or those in which the walking path is not straight. For example, in one study, gait parameters in fast walking were obtained through inertial sensors mounted on the upper body limbs [75]. Since this task demands upper limb movements for compensation, gait measures obtained from upper body motions might be more accurate compared with those obtained from the feet. Moreover, in some of studies, participants had to change their walking direction according to a curvilinear path [106] or to avoid obstacles [103], [104], in which the measurement instruments should not limit the walking area.

Furthermore, wearable sensors are less expensive than non-wearable sensors and do not require excessive space for normal operation. They can be used outside of laboratory settings and can be integrated with every day devices such as smart watches and phones [114]. On the other hand, wearable sensors are susceptible to noise and interference from external factors [114]. Moreover, they need to be mounted on the participant's body, which may be uncomfortable or intrusive [114].

3) BALANCE ASSESSMENT MEASURES

The most common measures of balance assessment in the reviewed literature were gait and sway parameters. Postural sway during standing, frequently assessed using CoP, is considered to be an effective measure of postural stability [186]. The centre of pressure is a point representing the projection of the centre of gravity on the base of support. Here, CoP parameters were most commonly measured since they are the gold standard assessment in the standing test. These parameters include time- and frequency-based ones. All except one sway parameters in the literature were time-based quantities. Compared with frequency-based parameters, time-based quantities enjoy better sensitivity and reliability. Moreover, frequency-based CoP parameters have limited sensitivity [119], [187].

In the dynamic balance tests, the balance assessment measures were gait parameters, which can be explained in two ways. First, in fNIRS studies, gait analysis is of great interest as gait performance relies on complex sensory-motor coordination requiring both automated and voluntary locomotive tasks [188]. Thus, gait parameters can provide a better understanding of sensory-motor coordination in walking. Second, neurodegenerative diseases and ageing can impact gait parameters [189]. In this regard, the effect of alterations to the brain structure can be detected through analysing gait parameters. In summary, gait parameters can be indicative of dynamic balance control in fNIRS studies.

B. RQ2- WHAT ALTERATIONS TO THE BALANCE CONTROL LOOP HAVE BEEN EXAMINED, IN THE REVIEWED fNIRS STUDIES?

In the reviewed literature, alterations to the balance control loop, including sensory manipulation and dual task interference, were considered in 49 studies. Maintaining balance requires a well coordinated action of the sensory, nervous, and motor systems. These systems affect each other mutually by cause and effect within a closed loop [65]. In the reviewed fNIRS studies, the effect of alteration to the balance control loop on both brain activity and balance performance was analysed based on objective quantitative data. Such an analysis can lead to a better understanding of relations and compensation strategies in balance control.

Here, sensory manipulation was applied in 10 studies with standing tests and 2 studies with dynamic tests including alteration to visual, vestibular, and somatosensory inputs. Alterations to the visual input were the most common manipulations including changes to the image elements or removing the input by closing eyes. Alteration to the vestibular input was also common in the literature, applied by unexpected movements of the support base or different neck and trunk rotation speeds. In two studies, alteration to the somatosensory system was applied by standing on two different surfaces; foam and solid. Such studies may reveal how the relative contribution of each sensory system changes depending on environmental conditions.

In the reviewed fNIRS studies, dual task interference was considered in 8 studies with static tests and 29 studies with dynamic tests. The second task was mainly a cognitive one with different levels of difficulty and neural demands; however, in two studies, a motor task was also considered. In dual task interference, alterations to the nervous system are caused by the allocation of attentional resources towards the performance of the cognitive task. The fNIRS measurements combined with balance assessment outcomes might reveal the contribution of cognitive resources to balance control.

The frequent use of dual task in fNIRS studies can be further explained by identifying the neural circuits engaged by the cognitive task in relation to those engaged during motor task performance. Moreover, the dual task interference replicates the features of real world daily activities when a person performs several motor and cognitive tasks concurrently. On the other hand, different dual task interference (e.g. second task, number of trials, and physical activity), participants' characteristics (e.g. background in the second task, level of stress, motor repertoire, and hemispheric asymmetry), and environmental conditions (e.g. time of day and room lighting) among or within studies hinder the interpretation of the findings [127]. Dual task interference is found to be of interest in fNIRS studies; however, there is no standardized dual task protocol that leads to a better interpretation of the dual task cost on behavioral and neurophysiological outcomes.

C. RQ3-HOW IS fNIRS USED WITH REGARDS TO CORTICAL AREAS IN QUANTITATIVE BALANCE ASSESSMENT STUDIES?

1) REGION OF INTEREST

In the reviewed literature, all cortical areas including the frontal, temporal, parietal, and occipital cortex were studied. Our findings suggest that RoIs are mainly chosen based on their functions in the task, alteration to the balance control loop, and participant cohort type. Accordingly, the frontal cortex and its sub-regions were the most commonly studied RoI, based on the dominant role of the frontal cortex in the balance function. Since the PFC plays an important role in cognitive functions [153], [181], this area was frequently studied in dual task tests. Moreover, measurement of PFC activity involve less motion artifacts and signal attenuation due to the slippage in hairs. Also, it is likely to be more effective in the case of motor-function related disability [190]. Overall, the frontal cortex is responsible for several tasks among which executive functions, voluntary movement, decision making, and cognitive behaviour [191] are essential for balance control.

After the frontal cortex, the parietal cortex was the second most commonly studied area in the reviewed literature, and some studies investigated temporal and occipital areas. The parietal cortex was studied in challenging tasks such as one-leg stance and backward walking, or those with sensory manipulation and dual task interference. This area was studied because of its fundamental role in spatial orientation, navigation, complex motor repertoire, and various somatic sensations from the body [155]. The temporal cortex, which embraces auditory and visual association areas [192], was mainly studied in articles including sensory manipulation. In two studies, occipital cortex activity was investigated in the presence of alterations to the visual elements because of its role in visual processing and interpretation such as determining, recognizing, and comparing objects to each other [193]. In summary, the frontal cortex was studied in almost all included articles because of its important role in balance control, and other cortical areas were included in some studies due to their specific roles in the tasks.

2) FNIRS PARAMETERS

In the reviewed articles, different numbers of fNIRS channels ranging from 3 to 64 were employed as reported in Table 6. Some studies used a few channels to measure from specific RoIs, whereas others used many channels to cover broader areas of the scalp; both approaches have advantages and limitations. Multi-channel units record the activity of more cortical regions; however, they suffer from lower sampling rates as a result of the signal multiplexing needed to distinguish between channels. This can have a negative impact on data quality. Moreover, low sampling rates preclude the ability to apply some of the recommended signal processing steps. A single channel, however, focuses on a single RoI. This limits the understanding of the network of regions involved and important changes across them that may occur in complex functions. In conclusion, the number of fNIRS channels should be decided by the specific research questions [182].

In the reviewed literature, 38 papers studied HbO_2 concentration, 28 papers studied both HbO_2 and HHb concentration, and two papers only studied HHb concentration. By definition, HbO_2 and HHb exist in equilibrium, such that an increase in one causes a stoichiometric decrease in the other. However, this explanation is only valid if local blood volume is constant, which is not necessarily true in some populations such as older people and neurological patients. Asymmetrical neural pathologies and vascular disease in these populations can affect haemodynamics. Here, many participant cohorts included older adults and neurological patients. Hence, additional measures such as the total haemoglobin (HbO_2+HHb), the tissue oxygenation index (the change in HbO_2 relative to the change in HHb), the ratio of HbO_2 to total haemoglobin, the difference between haemoglobin species (HbO_2 – HHb), and the regional cortical activation ratio (HbO_2 measured at a single channel over the RoI divided by average HbO_2 of all channels multiplied by 100) could have been calculated to provide additional insight into task activity and performance. However, to choose only from HbO_2 and HHb, the former is indicated to be more desirable according to the results. This parameter is shown to be more expressive of change due to a higher signal-to noise ratio than HHb [182].

Out of 68 studies in the reviewed literature, 14 studies reported three wavelengths, 43 papers reported two wavelengths, and 11 papers have not reported the wavelengths considered for fNIRS. According to the reported wavelengths, a range of 690 to 850 nm was used. (Wavelengths used in each study are shown in Table 6.) Instrumental configurations such as wavelength selection can influence the signal quality; however, it cannot be easily changed by the operator. Hence, it is important to carefully report them in sufficient detail and follow the manufacturers' instructions. To reduce cross-talk, for example incorrect separation of changes in HbO_2 and HHb which heavily depends on the wavelength selection, an optimal combination of wavelengths should be used [28]. Even though there is currently no consensus as to which combination of wavelengths is optimal [182], the degree of cross-talk has been deemed to be relatively minimal when using one wavelength >730 nm and another <720 nm [194]. Commonly used commercial systems do not allow changing these parameters and typically report one wavelength between 705 nm and 760 nm and another around 850 nm [24].

D. RQ4-WHAT RELATIONSHIPS HAVE BEEN FOUND BETWEEN CORTICAL ACTIVITY AND BALANCE PERFORMANCE IN THE REVIEWED LITERATURE?

In the reviewed literature, the relationships between activity of cortical areas and balance assessment measures were investigated. These findings can help in developing a better understanding of the neuromotor control of balance; however, the number of papers studying these relationships is limited to 22, out of 68. Moreover, these findings are limited to the relationships between balance measures and a small number of frontal areas including the PFC, SMA, premotor cortex, primary somatosensory cortex, frontal gyri, and primary somatosensory cortex. Meanwhile, more investigations on the role of other cortical areas in balance control are required. Hence, fNIRS studies on the relationships between other sub-regions of the frontal cortex and balance performance parameters are needed.

There are several differences among the included studies investigating the relationships between cortical activity and balance measures, and their results cannot be generalized. First, each relationship is found through a specific balance test and/or study design. Even among studies including similar balance tests, different balance parameters were considered. For example, in different studies including walking tasks, different balance parameters such as stride duration, length, and frequency were considered. Besides, the relationships were mainly found between different populations, which might lead to inconsistent results. For example, the relationships between PFC activity and gait velocity are found to be in opposition between healthy adults and those with NGA [6]. Contradictory relationships were also found between stride length and PFC activity among older people [80] and adults with chronic post-stroke hemispheres [73]. In summary, a general outline for the relationship between brain activity patterns and balance control cannot be extracted from the associations found in the reviewed literature. Among the aforementioned studies, most relationships were found based on correlation analysis. This method is influenced by the range of observations, cannot be interpreted as causal, and assumes a linear association [195]. On the other hand, more comprehensive methods such as data fusion or machine learning might be better suited methods for discovering the neuromotor control of balance in humans.

E. RQ5-WHAT TYPES OF PARTICIPANT COHORTS ARE INVESTIGATED IN fNIRS STUDIES ON BALANCE CONTROL?

Two groups of clinical and non-clinical cohorts were studied in the reviewed articles. The factors studied among non-clinical cohorts included gender, age, fear of falling in older people, working memory capacity, and prior physical activity. Neurological disorders, diabetes, chronic obstructive pulmonary disease, and musculoskeletal disorders were the factors studied among clinical cohorts. According to the reviewed articles, the brain structure, neural mapping, cortical activation, and subsequently balance performance can change due to long-term factors such as prior physical activity, neurological disorders, chronic diseases, and injuries. Moreover, the brain structure and balance performance can be different between people based on biological and psychological factors such as age and gender. fNIRS studies on these factors can be useful to decode their effect on the brain activity and consequent changes in balance performance.

In the reviewed literature, ageing and neurological disorders were the most common factors among non-clinical and clinical cohorts, respectively. Older people and neurological patients are susceptible to balance disorders and risk of falling. Therefore, studying fNIRS in these populations might help in better understanding of their neuromotor control. This, in turn, can help with early detection of balance disorder and lead to better intervention and rehabilitation methods.

F. LIMITATIONS

We acknowledge some limitations in the reviewed literature. First, the included studies were different in additional factors, such as balance test conditions, number and duration of trials, which might have affected the results. Second, participants' co-factors such as motor repertoire, physical activity, practice and skill levels, general health conditions, and chronic disease, which can affect cortical activity, were beyond the scope of this review. Third, the fNIRS cap and band in long experiments might cause discomfort, extra pain, perspiration, or vasodilation, which contaminate the signal [196]. The recorded cortical activity could be biased by attention to the discomfort and further limit the tolerable duration of the testing time. Furthermore, the presence and type of hair (colour, thickness, and density) between the scalp and the fNIRS optodes can generate large motion artefacts through reflection of light and increased decoupling of the optodes from the scalp [197]. The number of channels was not mentioned in some studies. It should also be noted that fNIRS is an indirect optical measurement technique that measures haemodynamic changes instead of neural activity. Accordingly, there is always a delay between an activity performed and a detected response; thus, in such decoding tasks, data analysis accuracy is compromised [198]. These factors may affect the accuracy and reliability of the results. Last but not least, small sample sizes in the reviewed articles are another limitation of the reviewed literature. Complementary studies and reviews are required to elucidate the influence of the above-mentioned factors on cortical activity and associated balance control.

G. FUTURE WORK

In this review, we summarized 68 fNIRS studies on quantitative balance assessment. The findings of these studies have led to a better understanding of neuromotor control of balance. Included articles varied in balance tests, alterations to the balance control loop, brain region of interest, participant cohort types, and fNIRS application and settings. In order to derive general theory of neuromotor control of balance in different participant cohorts and under different conditions, more studies are needed. fNIRS research on balance performance is in its relative infancy and requires to be expanded from different aspects. First, balance tests in the reviewed literature were limited to standing- and walking-base tasks; however, future fNIRS studies can consider a broader range of and more challenging balance tasks. Moreover, both static and dynamic tasks can be used in a particular study and compared for cortical activation. In future work, alterations to the balance control loop can include further strategies such as playing computer games for dual task and additional somatosensory manipulations. Besides, a broader range of populations such as low vision people or people with other chronic musculoskeletal system disorders can be studied. The effect of confounding variables such as age, biological sex, physical activity levels, and regular sporting activity might be addressed further. Moreover, in future studies, larger brain areas and a greater number of channels must be used in order to show a clearer picture of cortical activation during balance tasks.

V. CONCLUSION

In summary, the results of this review showed that the main balance tests in fNIRS studies include standing and walking tasks. In these tests, standing balance control is mainly measured through sway parameters using force platforms, and walking performance is evaluated through gait parameters, mostly assessed by floor sensors or inertial sensors. Moreover, in several studies participants' balance was challenged by alterations to the balance control loop. These alterations were mainly sensory manipulation and dual task interference in some standing and dynamic tests. Our findings also showed that the effects of biological, psychological, musculoskeletal disorders, and long-term factors on brain activity and balance performance have been studied among different populations. Among these factors, age and neurological disorders were the most common. fNIRS parameters studied in the reviewed literature were mainly oxygenated haemoglobin; however, total haemoglobin and deoxygenated haemoglobin were also included in some studies. In addition, fNIRS was utilized to measure activity in different brain cortical areas, most commonly frontal cortex. Furthermore, in some studies, the relationships between sub-regions of frontal cortex and balance measures were investigated and found. Taken together, our findings support that fNIRS measurement in conjunction with quantitative balance assessment have been employed to provide a better understanding of neuromotor control of balance in different populations.

REFERENCES

[1] R. J. Peterka, "Sensorimotor integration in human postural control," *J. Neurophysiol.*, vol. 88, no. 3, pp. 1097–1118, Sep. 2002.

[2] 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, Aug. 2017, Art. no. 041403.

[3] A. Bishnoi, R. Holtzer, and M. E. Hernandez, "Brain activation changes while walking in adults with and without neurological disease: Systematic review and meta-analysis of functional near-infrared spectroscopy studies," *Brain Sci.*, vol. 11, no. 3, p. 291, Feb. 2021.

[4] F. B. Horak, "Clinical assessment of balance disorders," *Gait Posture*, vol. 6, no. 1, pp. 76–84, Aug. 1997.

[5] A. B. Rosen, J. M. Yentes, M. L. McGrath, A. C. Maerlender, S. A. Myers, and M. Mukherjee, "Alterations in cortical activation among individuals with chronic ankle instability during single-limb postural control," *J. Athletic Training*, vol. 54, no. 6, pp. 718–726, Jun. 2019.

[6] R. Holtzer, J. Verghese, G. Allali, M. Izzetoglu, C. Wang, and J. R. Mahoney, "Neurological gait abnormalities moderate the functional brain signature of the posture first hypothesis," *Brain Topography*, vol. 29, no. 2, pp. 334–343, Mar. 2016.

[7] M. Ghahramani, "Fall risk assessment in older people," *Int. J. Eng. Sci.*, vol. 5, no. 11, pp. 1–14, Nov. 2016.

[8] R. J. Peterka, "Sensory integration for human balance control," *Handbook Clin. Neurol.*, vol. 159, pp. 27–42, 2018.

[9] A. D. Kuo, "An optimal state estimation model of sensory integration in human postural balance," *J. Neural Eng.*, vol. 2, no. 3, pp. S235–S249, Sep. 2005.

[10] B. G. Rasman, P. A. Forbes, R. Tisserand, and J.-S. Blouin, "Sensorimotor manipulations of the balance control loop–beyond imposed external perturbations," *Frontiers Neurol.*, vol. 9, p. 899, Oct. 2018.

[11] A. Mierau, B. Pester, T. Hülsdünker, K. Schiecke, H. K. Struder, and H. Witte, "Cortical correlates of human balance control," *Brain Topography*, vol. 30, no. 4, pp. 434–446, Jul. 2017.

[12] 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.

[13] S. Cutini and S. Brigadoi, "Unleashing the future potential of functional near-infrared spectroscopy in brain sciences," *J. Neurosci. Methods*, vol. 232, pp. 152–156, Jul. 2014.

[14] S. Lloyd-Fox, A. Blasi, and C. E. Elwell, "Illuminating the developing brain: The past, present and future of functional near infrared spectroscopy," *Neurosci. Biobehav. Rev.*, vol. 34, no. 3, pp. 269–284, Feb. 2010.

[15] M. Smith, "Shedding light on the adult brain: A review of the clinical applications of near-infrared spectroscopy," *Phil. Trans. Roy. Soc. A, Math., Phys. Eng. Sci.*, vol. 369, no. 1955, pp. 4452–4469, Nov. 2011.

[16] J. Saliba, H. Bortfeld, D. J. Levitin, and J. S. Oghalai, "Functional near-infrared spectroscopy for neuroimaging in cochlear implant recipients," *Hearing Res.*, vol. 338, pp. 64–75, Aug. 2016.

[17] F. Herold, P. Wiegel, F. Scholkmann, and N. Müller, "Applications of functional near-infrared spectroscopy (fNIRS) neuroimaging in exercise–cognition science: A systematic, methodology-focused review," *J. Clin. Med.*, vol. 7, no. 12, p. 466, Nov. 2018.

[18] A. Sathe, S. Shenoy, and P. K. Sathe, "Evaluation of cerebral cortex activation during balance tasks using fNIRS: A systematic review," *Trends Sport Sci.*, vol. 28, no. 2, pp. 93–107, 2021.

[19] R. Fernandez 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] X.-S. Hu, K.-S. Hong, and S. S. Ge, "fNIRS-based online deception decoding," *J. Neural Eng.*, vol. 9, no. 2, Apr. 2012, Art. no. 026012.

[21] M. M. Plichta, M. J. Herrmann, C. G. Baehne, A.-C. Ehlis, M. M. Richter, P. Pauli, and A. J. Fallgatter, "Event-related functional near-infrared spectroscopy (fNIRS): Are the measurements reliable?" *NeuroImage*, vol. 31, no. 1, pp. 116–124, May 2006.

[22] G. Strangman, J. P. Culver, J. H. Thompson, and D. A. Boas, "A quantitative comparison of simultaneous BOLD fMRI and NIRS recordings during functional brain activation," *Neuroimage*, vol. 17, pp. 719–731, Oct. 2002.

[23] V. Gramigna, G. Pellegrino, A. Cerasa, S. Cutini, R. Vasta, G. Olivadese, I. Martino, and A. Quattrone, "Near-infrared spectroscopy in gait disorders: Is it time to begin?" *Neurorehabilitation Neural Repair*, vol. 31, no. 5, pp. 402–412, May 2017.

[24] P. H. S. 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, May 2019, Art. no. e6833.

[25] M. Izzetoglu and R. Holtzer, "Effects of processing methods on fNIRS signals assessed during active walking tasks in older adults," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 3, pp. 699–709, Mar. 2020.

[26] R. F. Rojas, X. Huang, J. Hernandez-Juarez, and K. Ou, "Physiological fluctuations show frequency-specific networks in fNIRS signals during resting state," in *Proc. 39th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2017, pp. 2550–2553.

[27] C. Udina, S. Avtzi, T. Durduran, R. Holtzer, A. L. Rosso, C. Castellano-Tejedor, L.-M. Perez, L. Soto-Bagaria, and M. Inzitari, "Functional near-infrared spectroscopy to study cerebral hemodynamics in older adults during cognitive and motor tasks: A review," *Frontiers Aging Neurosci.*, vol. 11, p. 367, Jan. 2020.

[28] F. Scholkmann, S. Kleiser, A. J. Metz, R. Zimmermann, J. M. Pavia, U. Wolf, and M. Wolf, "A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology," *NeuroImage*, vol. 85, pp. 6–27, Jan. 2014.

[29] H. Khan, N. Naseer, A. Yazidi, P. K. Eide, H. W. Hassan, and P. Mirtaheri, "Analysis of human gait using hybrid EEG-fNIRS-based BCI system: A review," *Frontiers Hum. Neurosci.*, vol. 14, Jan. 2021, Art. no. 613254.

[30] 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," *Neurorehabil. Neural Repair*, vol. 35, no. 9, pp. 755–768, Sep. 2021.

[31] O. J. Surgent, O. I. Dadalko, K. A. Pickett, and B. G. Travers, "Balance and the brain: A review of structural brain correlates of postural balance and balance training in humans," *Gait Posture*, vol. 71, pp. 245–252, Jun. 2019.

[32] E. Bressel, J. C. Yonker, J. Kras, and E. M. Heath, "Comparison of static and dynamic balance in female collegiate soccer, basketball, and gymnastics athletes," *J. Athletic Training*, vol. 42, no. 1, p. 42, 2007.

[33] K. M. Sibley, M. K. Beauchamp, K. Van Ooteghem, M. Paterson, and K. D. Wittmeier, "Components of standing postural control evaluated in pediatric balance measures: A scoping review," *Arch. Phys. Med. Rehabil.*, vol. 98, no. 10, pp. 2066–2078, Oct. 2017.

[34] M. Hinderaker, B. Sylcott, K. Williams, and C.-C. Lin, "Aging affects the ability to process the optic flow stimulations: A functional near-infrared spectrometry study," *J. Motor Behav.*, vol. 52, no. 4, pp. 466–473, Jul. 2020.

[35] G. St-Amant, T. Rahman, N. Polskaia, S. Fraser, and Y. Lajoie, "Unveilling the cerebral and sensory contributions to automatic postural control during dual-task standing," *Hum. Movement Sci.*, vol. 70, Apr. 2020, Art. no. 102587.

[36] I. Helmich, J. Coenen, S. Henckert, E. Pardalis, S. Schupp, and H. Lausberg, "Reduced frontopolar brain activation characterizes concussed athletes with balance deficits," *NeuroImage, Clin.*, vol. 25, Jan. 2020, Art. no. 102164.

[37] T. Tanimura, H. Takada, A. Sugiura, F. Kinoshita, and M. Takada, "Effects of the low-resolution 3D video clip on cerebrum blood flow dynamics," *Adv. Sci., Technol. Eng. Syst. J.*, vol. 4, no. 2, pp. 380–386, 2019.

[38] C. W. Hoppes, P. J. Sparto, S. L. Whitney, J. M. Furman, and T. J. Huppert, "Changes in cerebral activation in individuals with and without visual vertigo during optic flow: A functional near-infrared spectroscopy study," *NeuroImage, Clin.*, vol. 20, pp. 655–663, Jan. 2018.

[39] 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, Feb. 2016.

[40] T. Nagasawa and H. Hagiwara, "Availability of body motion and facial information for evaluating visual and auditory attention," *Proc. Manuf.*, vol. 3, pp. 5118–5125, Jan. 2015.

[41] H. Karim, S. I. Fuhrman, P. Sparto, J. Furman, and T. Huppert, "Functional brain imaging of multi-sensory vestibular processing during computerized dynamic posturography using near-infrared spectroscopy," *NeuroImage*, vol. 74, pp. 318–325, Jul. 2013.

[42] C. A. Reed, C. K. DuBois, K. A. Hutchison, T. J. Huppert, and S. M. Monfort, "Influence of serial subtraction tasks on transient characteristics of postural control," *Hum. Movement Sci.*, vol. 83, Jun. 2022, Art. no. 102950.

[43] R. J. St George, M. R. Hinder, R. Puri, E. Walker, and M. L. Callisaya, "Functional near-infrared spectroscopy reveals the compensatory potential of pre-frontal cortical activity for standing balance in young and older adults," *Neuroscience*, vol. 452, pp. 208–218, Jan. 2021.

[44] H. Fujita, K. Kasubuchi, S. Wakata, M. Hiyamizu, and S. Morioka, "Role of the frontal cortex in standing postural sway tasks while dual-tasking: A functional near-infrared spectroscopy study examining working memory capacity," *BioMed Res. Int.*, vol. 2016, pp. 1–10, Oct. 2016.

[45] I. Helmich, A. Berger, and H. Lausberg, "Neural control of posture in individuals with persisting postconcussion symptoms," *Med. Sci. Sports Exercise*, vol. 48, no. 12, pp. 2362–2369, 2016.

[46] M. Saraiva, S. Paszkiel, J. P. Vilas-Boas, and M. A. Castro, "Influence of cognitive task difficulty in postural control and hemodynamic response in the prefrontal cortex during static postural standing," *Appl. Sci.*, vol. 12, no. 13, p. 6363, Jun. 2022.

[47] Y. Li, Z. Xu, H. Xie, R. Fu, W. L. A. Lo, X. Cheng, J. Yang, L. Ge, Q. Yu, and C. Wang, "Changes in cortical activation during upright stance in individuals with chronic low back pain: An fNIRS study," *Frontiers Hum. Neurosci.*, vol. 17, Feb. 2023, Art. no. 1085831.

[48] M. Saraiva, J. P. Fuentes-García, J. P. Vilas-Boas, and M. A. Castro, "Relationship between physical activity level and sleep quality with postural control and hemodynamic response in the prefrontal cortex during dual-task performance," *Physiol. Behav.*, vol. 255, Oct. 2022, Art. no. 113935.

[49] X.-P. Chen, L.-J. Wang, X.-Q. Chang, K. Wang, H.-F. Wang, M. Ni, W.-X. Niu, and M. Zhang, "Tai chi and yoga for improving balance on one leg: A neuroimaging and biomechanics study," *Frontiers Neurol.*, vol. 12, Oct. 2021, Art. no. 746599.

[50] R. Ono, Y. Matsuura, K. Nakane, and H. Takada, "Physical effects of motion sickness for comfortable VR viewing," *IEEJ Trans. Electron., Inf. Syst.*, vol. 141, no. 9, pp. 940–947, 2021.

[51] Y. Chen, Y. Yu, R. Niu, and Y. Liu, "Selective effects of postural control on spatial vs. Nonspatial working memory: A functional near-infrared spectral imaging study," *Frontiers Hum. Neurosci.*, vol. 12, p. 243, Jun. 2018.

[52] G. St-Amant, T. Salzman, L. Michaud, N. Polskaia, S. Fraser, and Y. Lajoie, "Hemodynamic responses of quiet standing simultaneously performed with different cognitive loads in older adults," *Hum. Movement Sci.*, vol. 82, Apr. 2022, Art. no. 102931.

[53] T. Mitsutake, M. Sakamoto, and E. Horikawa, "Effect of neck and trunk rotation speeds on cerebral cortex activity and standing postural stability: A functional near-infrared spectroscopy study," *J. Phys. Therapy Sci.*, vol. 27, no. 9, pp. 2817–2819, 2015.

[54] Z. Wang and K. M. Newell, "Asymmetry of foot position and weight distribution channels the inter-leg coordination dynamics of standing," *Exp. Brain Res.*, vol. 222, no. 4, pp. 333–344, Oct. 2012.

[55] K. Berg and K. E. Norman, "Functional assessment of balance and gait," *Clinics Geriatric Med.*, vol. 12, no. 4, pp. 705–723, Nov. 1996.

[56] D. J. Lanska, "The romberg sign and early instruments for measuring postural sway," *Seminars Neurol.*, vol. 22, no. 4, pp. 409–418, 2002.

[57] E. S. Hile, J. S. Brach, S. Perera, D. M. Wert, J. M. VanSwearingen, and S. A. Studenski, "Interpreting the need for initial support to perform tandem stance tests of balance," *Phys. Therapy*, vol. 92, no. 10, pp. 1316–1328, Oct. 2012.

[58] F. B. Horak, "Clinical measurement of postural control in adults," *Phys. Therapy*, vol. 67, no. 12, pp. 1881–1885, Dec. 1987.

[59] S. Lord and D. Sturnieks, "The physiology of falling: Assessment and prevention strategies for older people," *J. Sci. Med. Sport*, vol. 8, no. 1, pp. 35–42, Mar. 2005.

[60] M. W. Rogers and M.-L. Mille, "Balance perturbations," *Handbook Clin. Neurol.*, vol. 159, pp. 85–105, Jan. 2018.

[61] O. Seidel, D. Carius, R. Kenville, and P. Ragert, "Motor learning in a complex balance task and associated neuroplasticity: A comparison between endurance athletes and nonathletes," *J. Neurophysiol.*, vol. 118, no. 3, pp. 1849–1860, Sep. 2017.

[62] M. Hiyamizu, H. Maeoka, A. Matsuo, and S. Morioka, "Effects of self-action observation on standing balance learning: A change of brain activity detected using functional near-infrared spectroscopy," *NeuroRehabilitation*, vol. 35, no. 3, pp. 579–585, Nov. 2014.

[63] N. Lehmann, Y.-A. Kuhn, M. Keller, N. Aye, F. Herold, B. Draganski, W. Taube, and M. Taubert, "Brain activation during active balancing and its behavioral relevance in younger and older adults: A functional near-infrared spectroscopy (fNIRS) study," *Frontiers Aging Neurosci.*, vol. 14, Mar. 2022, Art. no. 828474.

[64] A. L. Rosso, M. Cenciarini, P. J. Sparto, P. J. Loughlin, J. M. Furman, and T. J. Huppert, "Neuroimaging of an attention demanding dual-task during dynamic postural control," *Gait Posture*, vol. 57, pp. 193–198, Sep. 2017.

[65] F. Herold, K. Orlowski, S. Börmel, and N. G. Müller, "Cortical activation during balancing on a balance board," *Human Movement Sci.*, vol. 51, pp. 51–58, Jan. 2017.

[66] M. Ferrari, S. Bisconti, M. Spezialetti, S. Basso Moro, C. Di Palo, G. Placidi, and V. Quaresima, "Prefrontal cortex activated bilaterally by a tilt board balance task: A functional near-infrared spectroscopy study in a semi-immersive virtual reality environment," *Brain Topography*, vol. 27, no. 3, pp. 353–365, May 2014.

[67] S. B. Moro, S. Bisconti, M. Muthalib, M. Spezialetti, S. Cutini, M. Ferrari, G. Placidi, and V. Quaresima, "A semi-immersive virtual reality incremental swing balance task activates prefrontal cortex: A functional near-infrared spectroscopy study," *NeuroImage*, vol. 85, pp. 451–460, Jan. 2014.

[68] V. S. Beretta, R. Vitório, P. Nóbrega-Sousa, N. R. Conceição, D. Orcioli-Silva, M. P. Pereira, and L. T. B. Gobbi, "Effect of different intensities of transcranial direct current stimulation on postural response to external perturbation in patients with Parkinson's disease," *Neurorehabil. Neural Repair*, vol. 34, no. 11, pp. 1009–1019, Nov. 2020.

[69] D. Orcioli-Silva, A. Islam, M. R. Baker, L. T. B. Gobbi, L. Rochester, and A. Pantall, "Bi-anodal transcranial direct current stimulation combined with treadmill walking decreases motor cortical activity in young and older adults," *Frontiers Aging Neurosci.*, vol. 13, Dec. 2021, Art. no. 739998.

[70] V. D. Belli, D. Orcioli-Silva, V. S. Beretta, R. Vitório, V. C. Zampier, P. Nóbrega-Sousa, N. R. D. Conceição, and L. T. B. Gobbi, "Prefrontal cortical activity during preferred and fast walking in young and older adults: An fNIRS study," *Neuroscience*, vol. 473, pp. 81–89, Oct. 2021.

[71] J.-H. Jang, S. Park, J. An, J.-D. Choi, I. C. Seol, G. Park, S. H. Lee, Y. Moon, W. Kang, E.-S. Jung, J.-Y. Cha, C.-Y. Kim, S. Kim, I. C. Jung, and H. Yoo, "Gait disturbance improvement and cerebral cortex rearrangement by acupuncture in Parkinson's disease: A pilot assessor-blinded, randomized, controlled, parallel-group trial," *Neurorehabil. Neural Repair*, vol. 34, no. 12, pp. 1111–1123, Dec. 2020.

[72] R. Vitorio, S. Stuart, and M. Mancini, "Executive control of walking in people with Parkinson's disease with freezing of gait," *Neurorehabil. Neural Repair*, vol. 34, no. 12, pp. 1138–1149, Dec. 2020.

[73] S. A. Chatterjee, E. J. Fox, J. J. Daly, D. K. Rose, S. S. Wu, E. A. Christou, K. A. Hawkins, D. M. Otzel, K. A. Butera, J. W. Skinner, and D. J. Clark, "Interpreting prefrontal recruitment during walking after stroke: Influence of individual differences in mobility and cognitive function," *Frontiers Hum. Neurosci.*, vol. 13, p. 194, Jun. 2019.

[74] B. R. Groff, P. Antonellis, K. K. Schmid, B. A. Knarr, and N. Stergiou, "Stride-time variability is related to sensorimotor cortical activation during forward and backward walking," *Neurosci. Lett.*, vol. 692, pp. 150–158, Jan. 2019.

[75] E. Al-Yahya, W. Mahmoud, D. Meester, P. Esser, and H. Dawes, "Neural substrates of cognitive motor interference during walking; peripheral and central mechanisms," *Frontiers Hum. Neurosci.*, vol. 12, p. 536, Jan. 2019.

[76] Y. Liu, Y. Yang, Y. Tsai, R. Wang, and C. Lu, "Brain activation and gait alteration during cognitive and motor dual task walking in stroke—A functional near-infrared spectroscopy study," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 12, pp. 2416–2423, Dec. 2018.

[77] R. Holtzer, C. J. George, M. Izzetoglu, and C. Wang, "The effect of diabetes on prefrontal cortex activation patterns during active walking in older adults," *Brain Cognition*, vol. 125, pp. 14–22, Aug. 2018.

[78] R. Holtzer, C. Schoen, E. Demetriou, J. R. Mahoney, M. Izzetoglu, C. Wang, and J. Verghese, "Stress and gender effects on prefrontal cortex oxygenation levels assessed during single and dual-task walking conditions," *Eur. J. Neurosci.*, vol. 45, no. 5, pp. 660–670, Mar. 2017.

[79] M. E. Hernandez, R. Holtzer, G. Chaparro, K. Jean, J. M. Balto, B. M. Sandroff, M. Izzetoglu, and R. W. Motl, "Brain activation changes during locomotion in middle-aged to older adults with multiple sclerosis," *J. Neurolog. Sci.*, vol. 370, pp. 277–283, Nov. 2016.

[80] R. Holtzer, J. R. Mahoney, M. Izzetoglu, C. Wang, S. England, and J. Verghese, "Online fronto-cortical control of simple and attention-demanding locomotion in humans," *NeuroImage*, vol. 112, pp. 152–159, May 2015.

[81] R. Beurskens, I. Helmich, R. Rein, and O. Bock, "Age-related changes in prefrontal activity during walking in dual-task situations: A fNIRS study," *Int. J. Psychophysiol.*, vol. 92, no. 3, pp. 122–128, Jun. 2014.

[82] M. J. Kurz, T. W. Wilson, and D. J. Arpin, "Stride-time variability and sensorimotor cortical activation during walking," *NeuroImage*, vol. 59, no. 2, pp. 1602–1607, Jan. 2012.

[83] Y. Koren, Y. Parmet, and S. Bar-Haim, "Treading on the unknown increases prefrontal activity: A pilot fNIRS study," *Gait Posture*, vol. 69, pp. 96–100, Mar. 2019.

[84] M. A. de Aratanha, J. B. Balardin, C. Cardoso do Amaral, S. S. Lacerda, T. A. S. Sowmy, T. J. Huppert, R. B. Thomaz, D. S. Speciali, B. Machado, and E. H. Kozasa, "The use of functional near infrared spectroscopy and gait analysis to characterize cognitive and motor processing in early-stage patients with multiple sclerosis," *Frontiers Neurol.*, vol. 13, Aug. 2022, Art. no. 937231.

[85] P. C. Thumm, I. Maidan, M. Brozgol, S. Shustak, E. Gazit, S. S. Shiratzki, H. Bernad-Elazari, Y. Beck, N. Giladi, J. M. Hausdorff, and A. Mirelman, "Treadmill walking reduces pre-frontal activation in patients with Parkinson's disease," *Gait Posture*, vol. 62, pp. 384–387, May 2018.

[86] C.-F. Lu, Y.-C. Liu, Y.-R. Yang, Y.-T. Wu, and R.-Y. Wang, "Maintaining gait performance by cortical activation during dual-task interference: A functional near-infrared spectroscopy study," *PLoS ONE*, vol. 10, no. 6, Jun. 2015, Art. no. e0129390.

[87] S. A. Hassan, M. A. Campos, K. T. Kasawara, L. V. Bonetti, K. K. Patterson, D. S. Beal, G. A. F. Fregonezi, M. B. Stanbrook, and W. D. Reid, "Changes in oxyhemoglobin concentration in the prefrontal cortex during cognitive-motor dual tasks in people with chronic obstructive pulmonary disease," *COPD, J. Chronic Obstructive Pulmonary Disease*, vol. 17, no. 3, pp. 289–296, May 2020.

[88] M. Lucas, M. E. Wagshul, M. Izzetoglu, and R. Holtzer, "Moderating effect of white matter integrity on brain activation during dual-task walking in older adults," *J. Gerontol., Ser. A*, vol. 74, no. 4, pp. 435–441, Mar. 2019.

[89] R. Vitorio, S. Stuart, L. T. B. Gobbi, L. Rochester, L. Alcock, and A. Pantall, "Reduced gait variability and enhanced brain activity in older adults with auditory cues: A functional near-infrared spectroscopy study," *Neurorehabil. Neural Repair*, vol. 32, no. 11, pp. 976–987, Nov. 2018.

[90] D. J. Clark, E. A. Christou, S. A. Ring, J. B. Williamson, and L. Doty, "Enhanced somatosensory feedback reduces prefrontal cortical activity during walking in older adults," *Journals Gerontol. Ser. A, Biol. Sci. Med. Sci.*, vol. 69, no. 11, pp. 1422–1428, Nov. 2014.

[91] R. Holtzer, M. Izzetoglu, M. Chen, and C. Wang, "Distinct fNIRS-derived HbO_2 trajectories during the course and over repeated walking trials under single- and dual-task conditions: Implications for within session learning and prefrontal cortex efficiency in older adults," *J. Gerontol., Ser. A*, vol. 74, no. 7, pp. 1076–1083, Jun. 2019.

[92] R. J. St George, O. Jayakody, R. Healey, M. Breslin, M. R. Hinder, and M. L. Callisaya, "Cognitive inhibition tasks interfere with dual-task walking and increase prefrontal cortical activity more than working memory tasks in young and older adults," *Gait Posture*, vol. 95, pp. 186–191, Jun. 2022.

[93] E. Hermand, M. Compagnat, O. Dupuy, J.-Y. Salle, J.-C. Daviet, and A. Perrochon, "Functional status is associated with prefrontal cortex activation in gait in subacute stroke patients: A functional near-infrared spectroscopy study," *Frontiers Neurol.*, vol. 11, Nov. 2020, Art. no. 559227.

[94] M. Saraiva, M. A. Castro, and J. P. Vilas-Boas, "The role of sleep quality and physical activity level on gait speed and brain hemodynamics changes in young adults—A dual-task study," *Eur. J. Invest. Health, Psychol. Educ.*, vol. 12, no. 11, pp. 1673–1681, Nov. 2022.

[95] P. Caliandro, M. Serrao, L. Padua, G. Silvestri, C. Iacovelli, C. Simbolotti, S. Mari, G. Reale, C. Casali, and P. M. Rossini, "Prefrontal cortex as a compensatory network in ataxic gait: A correlation study between cortical activity and gait parameters," *Restorative Neurol. Neurosci.*, vol. 33, no. 2, pp. 177–187, 2015.

[96] A. Mirelman, I. Maidan, H. Bernad-Elazari, F. Nieuwhof, M. Reelick, N. Giladi, and J. M. Hausdorff, "Increased frontal brain activation during walking while dual tasking: An fNIRS study in healthy young adults," *J. Neuroeng. Rehabil.*, vol. 11, pp. 1–7, Dec. 2014.

[97] M. Ghahramani, F. Naghdy, D. Stirling, G. Naghdy, J. Potter, and M. Roach, "Assessing the risk of fall in older people through turning test," in *Proc. IEEE Int. Symp. Med. Meas. Appl. (MeMeA)*, Jun. 2018, pp. 1–6.

[98] L. Tesio and V. Rota, "The motion of body center of mass during walking: A review oriented to clinical applications," *Frontiers Neurol.*, vol. 10, p. 999, Sep. 2019.

[99] C. A. Fukuchi, R. K. Fukuchi, and M. Duarte, "Effects of walking speed on gait biomechanics in healthy participants: A systematic review and meta-analysis," *Systematic Rev.*, vol. 8, no. 1, pp. 1–11, Dec. 2019.

[100] M. Lee, J. Kim, J. Son, and Y. Kim, "Kinematic and kinetic analysis during forward and backward walking," *Gait Posture*, vol. 38, no. 4, pp. 674–678, Sep. 2013.

[101] 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 Rel. Disorders*, vol. 86, pp. 10–14, May 2021.

[102] 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 Topography*, vol. 30, no. 4, pp. 531–538, Jul. 2017.

[103] A. Mirelman, I. Maidan, H. Bernad-Elazari, S. Shustack, N. Giladi, and J. M. Hausdorff, "Effects of aging on prefrontal brain activation during challenging walking conditions," *Brain Cognition*, vol. 115, pp. 41–46, Jul. 2017.

[104] D. Orcioli-Silva, R. Vitório, P. Nóbrega-Sousa, V. S. Beretta, N. R. D. Conceição, A. S. Oliveira, M. P. Pereira, and L. T. B. Gobbi, "Cortical activity underlying gait improvements achieved with dopaminergic medication during usual walking and obstacle avoidance in Parkinson disease," *Neurorehabil. Neural Repair*, vol. 35, no. 5, pp. 406–418, May 2021.

[105] M.-I.-B. Lin and K.-H. Lin, "Walking while performing working memory tasks changes the prefrontal cortex hemodynamic activations and gait kinematics," *Frontiers Behav. Neurosci.*, vol. 10, p. 92, May 2016.

[106] V. Belluscio, G. Casti, M. Ferrari, V. Quaresima, M. S. Sappia, J. M. Horschig, and G. Vannozzi, "Modifications in prefrontal cortex oxygenation in linear and curvilinear dual task walking: A combined fNIRS and IMUs study," *Sensors*, vol. 21, no. 18, p. 6159, Sep. 2021.

[107] Y. Chen, A. Wan, M. Mao, W. Sun, Q. Song, and D. Mao, "Tai chi practice enables prefrontal cortex bilateral activation and gait performance prioritization during dual-task negotiating obstacle in older adults," *Frontiers Aging Neurosci.*, vol. 14, Nov. 2022, Art. no. 1000427.

[108] Y. Chen, Z. Cao, M. Mao, W. Sun, Q. Song, and D. Mao, "Increased cortical activation and enhanced functional connectivity in the prefrontal cortex ensure dynamic postural balance during dual-task obstacle negotiation in the older adults: A fNIRS study," *Brain Cognition*, vol. 163, Nov. 2022, Art. no. 105904.

[109] K. A. Hawkins, E. J. Fox, J. J. Daly, D. K. Rose, E. A. Christou, T. E. McGuirk, D. M. Otzel, K. A. Butera, S. A. Chatterjee, and D. J. Clark, "Prefrontal over-activation during walking in people with mobility deficits: Interpretation and functional implications," *Hum. Movement Sci.*, vol. 59, pp. 46–55, Jun. 2018.

[110] L. Z. Rubenstein, K. R. Josephson, P. R. Trueblood, K. Yeung, J. O. Harker, and A. S. Robbins, "The reliability and validity of an obstacle course as a measure of gait and balance in older adults," *Aging Clin. Experim. Res.*, vol. 9, nos. 1–2, pp. 127–135, Feb. 1997.

[111] M. Mancini and F. B. Horak, "The relevance of clinical balance assessment tools to differentiate balance deficits," *Eur. J. Phys. Rehabil. Med.*, vol. 46, no. 2, p. 239, 2010.

[112] B. Chen, P. Liu, F. Xiao, Z. Liu, and Y. Wang, "Review of the upright balance assessment based on the force plate," *Int. J. Environ. Res. Public Health*, vol. 18, no. 5, p. 2696, Mar. 2021.

[113] R. A. Clark, A. L. Bryant, Y. Pua, P. McCrory, K. Bennell, and M. Hunt, "Validity and reliability of the Nintendo Wii balance board for assessment of standing balance," *Gait Posture*, vol. 31, no. 3, pp. 307–310, Mar. 2010.

[114] A. Muro-de-la-Herran, B. Garcia-Zapirain, and A. Mendez-Zorrilla, "Gait analysis methods: An overview of wearable and non-wearable systems, highlighting clinical applications," *Sensors*, vol. 14, no. 2, pp. 3362–3394, Feb. 2014.

[115] A. B. Sorsdahl, R. Moe-Nilssen, and L. I. Strand, "Test–retest reliability of spatial and temporal gait parameters in children with cerebral palsy as measured by an electronic walkway," *Gait Posture*, vol. 27, no. 1, pp. 43–50, Jan. 2008.

[116] R. Boulic, J.-F. Hétu, and D. Thalmann, "The Vicon motion capture system," in *Virtual Worlds Multimedia*. Cham, Switzerland: Springer, 2002, pp. 241–260.

[117] L. Ruiz-Ruiz, A. R. Jimenez, G. Garcia-Villamil, and F. Seco, "Detecting fall risk and frailty in elders with inertial motion sensors: A survey of significant gait parameters," *Sensors*, vol. 21, no. 20, p. 6918, Oct. 2021.

[118] B. E. Maki, P. J. Holliday, and G. R. Fernie, "Aging and postural control: A comparison of spontaneous- and induced-sway balance tests," *J. Amer. Geriatrics Soc.*, vol. 38, no. 1, pp. 1–9, Jan. 1990.

[119] S. Nejc, R. Jernej, S. Loefler, and H. Kern, "Sensitivity of body sway parameters during quiet standing to manipulation of support surface size," *J. sports Sci. Med.*, vol. 9, no. 3, p. 431, 2010.

[120] D. Lin, H. Seol, M. A. Nussbaum, and M. L. Madigan, "Reliability of COP-based postural sway measures and age-related differences," *Gait Posture*, vol. 28, no. 2, pp. 337–342, Aug. 2008.

[121] A. Yelnik and I. Bonan, "Clinical tools for assessing balance disorders," *Neurophysiologie Clinique/Clin. Neurophysiol.*, vol. 38, no. 6, pp. 439–445, Dec. 2008.

[122] S. Díaz, J. B. Stephenson, and M. A. Labrador, "Use of wearable sensor technology in gait, balance, and range of motion analysis," *Appl. Sci.*, vol. 10, no. 1, p. 234, Dec. 2019.

[123] R. Holtzer, R. Kraut, M. Izzetoglu, and K. Ye, "The effect of fear of falling on prefrontal cortex activation and efficiency during walking in older adults," *GeroScience*, vol. 41, no. 1, pp. 89–100, Feb. 2019.

[124] 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, Apr. 2015.

[125] L. Nashner, "Evaluation of postural stability, movement, and control," *Clin. Exercise Physiol.*, vol. 1, pp. 199–230, Jan. 1994.

[126] J. Ruffieux, M. Keller, B. Lauber, and W. Taube, "Changes in standing and walking performance under dual-task conditions across the lifespan," *Sports Med.*, vol. 45, no. 12, pp. 1739–1758, Dec. 2015.

[127] M. Kahya, S. Moon, M. Ranchet, R. R. Vukas, K. E. Lyons, R. Pahwa, A. Akinwuntan, and H. Devos, "Brain activity during dual task gait and balance in aging and age-related neurodegenerative conditions: A systematic review," *Experim. Gerontol.*, vol. 128, Dec. 2019, Art. no. 110756.

[128] D. F. Collins, K. M. Refshauge, G. Todd, and S. C. Gandevia, "Cutaneous receptors contribute to kinesthesia at the index finger, elbow, and knee," *J. Neurophysiol.*, vol. 94, no. 3, pp. 1699–1706, 2005.

[129] J. T. Mohl, J. M. Pearson, and J. M. Groh, "Monkeys and humans implement causal inference to simultaneously localize auditory and visual stimuli," *J. Neurophysiol.*, vol. 124, no. 3, pp. 715–727, Sep. 2020.

[130] W. M. Paulus, A. Straube, and T. Brandt, "Visual stabilization of posture: Physiological stimulus characteristics and clinical aspects," *Brain*, vol. 107, no. 4, pp. 1143–1163, 1984.

[131] J. L. Zettel, A. Holbeche, W. E. McIlroy, and B. E. Maki, "Redirection of gaze and switching of attention during rapid stepping reactions evoked by unpredictable postural perturbation," *Exp. Brain Res.*, vol. 165, no. 3, pp. 392–401, Sep. 2005.

[132] D. E. Angelaki and K. E. Cullen, "Vestibular system: The many facets of a multimodal sense," *Annu. Rev. Neurosci.*, vol. 31, no. 1, pp. 125–150, Jul. 2008.

[133] M. A. Riley and S. Clark, "Recurrence analysis of human postural sway during the sensory organization test," *Neurosci. Lett.*, vol. 342, nos. 1–2, pp. 45–48, May 2003.

[134] K. H. Jawabri and S. Sharma, "Physiology, cerebral cortex functions," in *StatPearls*. St. Petersburg, FL, USA: StatPearls, 2021.

[135] E. Wittenberg, J. Thompson, C. S. Nam, and J. R. Franz, "Neuroimaging of human balance control: A systematic review," *Frontiers Hum. Neurosci.*, vol. 11, p. 170, Apr. 2017.

[136] D. E. J. Linden, "The working memory networks of the human brain," *Neuroscientist*, vol. 13, no. 3, pp. 257–267, Jun. 2007.

[137] S. J. Gilbert and P. W. Burgess, "Executive function," *Current Biol.*, vol. 18, no. 3, pp. R110–R114, 2008.

[138] J. Stretton and P. J. Thompson, "Frontal lobe function in temporal lobe epilepsy," *Epilepsy Res.*, vol. 98, no. 1, pp. 1–13, Jan. 2012.

[139] E. K. Miller and J. D. Cohen, "An integrative theory of prefrontal cortex function," *Annu. Rev. Neurosci.*, vol. 24, no. 1, pp. 167–202, Mar. 2001.

[140] T. L. Luks, G. V. Simpson, C. L. Dale, and M. G. Hough, "Preparatory allocation of attention and adjustments in conflict processing," *NeuroImage*, vol. 35, no. 2, pp. 949–958, Apr. 2007.

[141] J.-W. Park, Y.-H. Kim, S. H. Jang, W. H. Chang, C.-H. Park, and S. T. Kim, "Dynamic changes in the cortico-subcortical network during early motor learning," *NeuroRehabilitation*, vol. 26, no. 2, pp. 95–103, Feb. 2010.

[142] R. Gupta and D. Tranel, "Memory, neural substrates," in *Encyclopedia of Human Behavior*. Amsterdam, The Netherlands: Elsevier, 2012, pp. 593–600.

[143] P. A. Chouinard and T. Paus, "The primary motor and premotor areas of the human cerebral cortex," *Neuroscientist*, vol. 12, no. 2, pp. 143–152, Apr. 2006.

[144] L. Almulla, I. Al-Naib, I. S. Ateeq, and M. Althobaiti, "Observation and motor imagery balance tasks evaluation: An fNIRS feasibility study," *PLoS ONE*, vol. 17, no. 3, Mar. 2022, Art. no. e0265898.

[145] A. N. Parks and J. B. Smaers, "The evolution of the frontal lobe in humans," in *Digital Endocasts*. Cham, Switzerland: Springer, 2018, pp. 205–218.

[146] P. Nachev, C. Kennard, and M. Husain, "Functional role of the supplementary and pre-supplementary motor areas," *Nature Rev. Neurosci.*, vol. 9, no. 11, pp. 856–869, Nov. 2008.

[147] P. E. Roland, B. Larsen, N. A. Lassen, and E. Skinhoj, "Supplementary motor area and other cortical areas in organization of voluntary movements in man," *J. Neurophysiol.*, vol. 43, no. 1, pp. 118–136, Jan. 1980.

[148] L. Banker and P. Tadi, "Neuroanatomy, precentral gyrus," StatPearls Publishing, Treasure Island, FL, USA, Tech. Rep., 2019. [Online]. Available: https://www.ncbi.nlm.nih.gov/books/NBK544218/

[149] D. A. Rosenbaum, *Human Motor Control*. New York, NY, USA: Academic, 2009.

[150] C. Lamm, C. Windischberger, U. Leodolter, E. Moser, and H. Bauer, "Evidence for premotor cortex activity during dynamic visuospatial imagery from single-trial functional magnetic resonance imaging and event-related slow cortical potentials," *NeuroImage*, vol. 14, no. 2, pp. 268–283, Aug. 2001.

[151] E. Marx, T. Stephan, A. Nolte, A. Deutschländer, K. C. Seelos, M. Dieterich, and T. Brandt, "Eye closure in darkness animates sensory systems," *NeuroImage*, vol. 19, no. 3, pp. 924–934, Jul. 2003.

[152] M. Göttlich, N. M. Jandl, J. F. Wojak, A. Sprenger, J. V. der Gablentz, T. F. Münte, U. M. Krämer, and C. Helmchen, "Altered resting-state functional connectivity in patients with chronic bilateral vestibular failure," *NeuroImage, Clin.*, vol. 4, pp. 488–499, Jan. 2014.

[153] M. Mihara, I. Miyai, M. Hatakenaka, K. Kubota, and S. Sakoda, "Role of the prefrontal cortex in human balance control," *NeuroImage*, vol. 43, no. 2, pp. 329–336, Nov. 2008.

[154] S. H. Lim, D. S. Dinner, P. K. Pillay, H. Lüders, H. H. Morris, G. Klem, E. Wyllie, and I. A. Awad, "Functional anatomy of the human supplementary sensorimotor area: Results of extraoperative electrical stimulation," *Electroencephalogr. Clin. Neurophysiol.*, vol. 91, no. 3, pp. 179–193, Sep. 1994.

[155] S. Teixeira, S. Machado, B. Velasques, A. Sanfim, D. Minc, C. Peressutti, J. Bittencourt, H. Budde, M. Cagy, R. Anghinah, L. F. Basile, R. Piedade, P. Ribeiro, C. Diniz, C. Cartier, M. Gongora, F. Silva, F. Manaia, and J. G. Silva, "Integrative parietal cortex processes: Neurological and psychiatric aspects," *J. Neurolog. Sci.*, vol. 338, nos. 1–2, pp. 12–22, Mar. 2014.

[156] D. M. Lloyd, F. P. McGlone, and G. Yosipovitch, "Somatosensory pleasure circuit: From skin to brain and back," *Experim. Dermatol.*, vol. 24, no. 5, pp. 321–324, May 2015.

[157] D. M. Wolpert, S. J. Goodbody, and M. Husain, "Maintaining internal representations: The role of the human superior parietal lobe," *Nature Neurosci.*, vol. 1, no. 6, pp. 529–533, Oct. 1998.

[158] L. Fogassi and G. Luppino, "Motor functions of the parietal lobe," *Current Opinion Neurobiol.*, vol. 15, no. 6, pp. 626–631, Dec. 2005.

[159] C.-C. Lin, J. W. Barker, P. J. Sparto, J. M. Furman, and T. J. Huppert, "Functional near-infrared spectroscopy (fNIRS) brain imaging of multisensory integration during computerized dynamic posturography in middle-aged and older adults," *Exp. Brain Res.*, vol. 235, no. 4, pp. 1247–1256, Apr. 2017.

[160] M. Zimmermann, R. B. Mars, F. P. de Lange, I. Toni, and L. Verhagen, "Is the extrastriate body area part of the dorsal visuomotor stream?" *Brain Struct. Function*, vol. 223, no. 1, pp. 31–46, Jan. 2018.

[161] K. Grill-Spector, T. Kushnir, T. Hendler, S. Edelman, Y. Itzchak, and R. Malach, "A sequence of object-processing stages revealed by fMRI in the human occipital lobe," *Hum. Brain Mapping*, vol. 6, no. 4, pp. 316–328, 1998.

[162] H. Niu, X. Li, Y. Chen, C. Ma, J. Zhang, and Z. Zhang, "Reduced frontal activation during a working memory task in mild cognitive impairment: A non-invasive near-infrared spectroscopy study," *CNS Neurosci. Therapeutics*, vol. 19, no. 2, pp. 125–131, Feb. 2013.

[163] J. D. Schaeffer, A. S. Yennu, K. C. Gandy, F. Tian, H. Liu, and H. Park, "An fNIRS investigation of associative recognition in the prefrontal cortex with a rapid event-related design," *J. Neurosci. Methods*, vol. 235, pp. 308–315, Sep. 2014.

[164] F. B. Haeussinger, T. Dresler, S. Heinzel, M. Schecklmann, A. J. Fallgatter, and A.-C. Ehlis, "Reconstructing functional near-infrared spectroscopy (fNIRS) signals impaired by extra-cranial confounds: An easy-to-use filter method," *NeuroImage*, vol. 95, pp. 69–79, Jul. 2014.

[165] T. J. Huppert, R. D. Hoge, S. G. Diamond, M. A. Franceschini, and D. A. Boas, "A temporal comparison of BOLD, ASL, and NIRS hemodynamic responses to motor stimuli in adult humans," *NeuroImage*, vol. 29, no. 2, pp. 368–382, Jan. 2006.

[166] S. E. MacPherson, L. H. Phillips, and S. D. Sala, "Age, executive function and social decision making: A dorsolateral prefrontal theory of cognitive aging," *Psychol. Aging*, vol. 17, no. 4, pp. 598–609, 2002.

[167] H. W. Lach and J. L. Parsons, "Impact of fear of falling in long term care: An integrative review," *J. Amer. Med. Directors Assoc.*, vol. 14, no. 8, pp. 573–577, Aug. 2013.

[168] J. H. Hollman, J. W. Youdas, and D. J. Lanzino, "Gender differences in dual task gait performance in older adults," *Amer. J. Men's Health*, vol. 5, no. 1, pp. 11–17, Jan. 2011.

[169] M. W. Voss, "Plasticity of brain networks in a randomized intervention trial of exercise training in older adults," *Frontiers Aging Neurosci.*, vol. 2, p. 32, Aug. 2010.

[170] L. Schlaffke, S. Lissek, M. Lenz, M. Brüne, G. Juckel, T. Hinrichs, P. Platen, M. Tegenthoff, and T. Schmidt-Wilcke, "Sports and brain morphology—A voxel-based morphometry study with endurance athletes and martial artists," *Neuroscience*, vol. 259, pp. 35–42, Feb. 2014.

[171] E. Koechlin, G. Basso, P. Pietrini, S. Panzer, and J. Grafman, "The role of the anterior prefrontal cortex in human cognition," *Nature*, vol. 399, no. 6732, pp. 148–151, May 1999.

[172] M. Montero-Odasso, H. Bergman, N. A. Phillips, C. H. Wong, N. Sourial, and H. Chertkow, "Dual-tasking and gait in people with mild cognitive Impairment. The effect of working memory," *BMC Geriatrics*, vol. 9, no. 1, pp. 1–8, Dec. 2009.

[173] P. X. Ku, N. A. A. Osman, and W. A. B. W. Abas, "Balance control in lower extremity amputees during quiet standing: A systematic review," *Gait Posture*, vol. 39, no. 2, pp. 672–682, Feb. 2014.

[174] K. Chan, W. Pang, C. H. Ee, Y. Ding, and P. Choo, "Epidemiology of falls among the elderly community dwellers in Singapore," *Singap. Med. J.*, vol. 38, no. 10, pp. 427–431, 1997.

[175] T. Asada, T. Kariya, T. Kinoshita, A. Asaka, S. Morikawa, M. Yoshioka, and T. Kakuma, "Predictors of fall-related injuries among community-dwelling elderly people with dementia," *Age Ageing*, vol. 25, no. 1, pp. 22–28, 1996.

[176] A. Zampogna, I. Mileti, E. Palermo, C. Celletti, M. Paoloni, A. Manoni, I. Mazzetta, G. Dalla Costa, C. Pérez-López, F. Camerota, L. Leocani, J. Cabestany, F. Irrera, and A. Suppa, "Fifteen years of wireless sensors for balance assessment in neurological disorders," *Sensors*, vol. 20, no. 11, p. 3247, Jun. 2020.

[177] M. Abtahi, S. B. Borgheai, R. Jafari, N. Constant, R. Diouf, Y. Shahriari, and K. Mankodiya, "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.

[178] E. Fisher, J.-C. Lee, K. Nakamura, and R. A. Rudick, "Gray matter atrophy in multiple sclerosis: A longitudinal study," *Ann. Neurol.*, vol. 64, no. 3, pp. 255–265, Sep. 2008.

[179] J. Hertel, "Functional anatomy, pathomechanics, and pathophysiology of lateral ankle instability," *J. Athletic Training*, vol. 37, no. 4, p. 364, 2002.

[180] Z. Arvanitakis, R. S. Wilson, J. A. Schneider, J. L. Bienias, D. A. Evans, and D. A. Bennett, "Diabetes mellitus and progression of rigidity and gait disturbance in older persons," *Neurology*, vol. 63, no. 6, pp. 996–1001, Sep. 2004.

[181] 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, Jul. 2018.

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

[183] M. S. Hossain, M. B. I. Reaz, M. E. H. Chowdhury, S. H. M. Ali, A. A. A. Bakar, S. Kiranyaz, A. Khandakar, M. Alhatou, and R. Habib, "Motion artifacts correction from EEG and fNIRS signals using novel multiresolution analysis," *IEEE Access*, vol. 10, pp. 29760–29777, 2022.

[184] A. M. Gentile, "Skill acquisition: Action, movement, and the neuromotor processes," in *Movement science: Foundations for Physical Therapy in Rehabilitation*. Rockville, MD, USA: Aspen Publishers, 1987.

[185] J. E. Visser, M. G. Carpenter, H. van der Kooij, and B. R. Bloem, "The clinical utility of posturography," *Clin. Neurophysiol.*, vol. 119, no. 11, pp. 2424–2436, Nov. 2008.

[186] J. M. Prado, T. A. Stoffregen, and M. Duarte, "Postural sway during dual tasks in young and elderly adults," *Gerontology*, vol. 53, no. 5, pp. 274–281, 2007.

[187] X. Qu and M. A. Nussbaum, "Effects of external loads on balance control during upright stance: Experimental results and model-based predictions," *Gait Posture*, vol. 29, no. 1, pp. 23–30, Jan. 2009.

[188] F. Delcomyn, "Neural basis of rhythmic behavior in animals," *Science*, vol. 210, no. 4469, pp. 492–498, Oct. 1980.

[189] P. Terrier and Y. Schutz, "How useful is satellite positioning system (GPS) to track gait parameters? A review," *J. NeuroEng. Rehabil.*, vol. 2, no. 1, pp. 1–11, Dec. 2005.

[190] N. Naseer and K.-S. Hong, "fNIRS-based brain-computer interfaces: A review," *Frontiers Hum. Neurosci.*, vol. 9, p. 3, Jan. 2015.

[191] S. Funahashi, "Prefrontal cortex and working memory processes," *Neuroscience*, vol. 139, no. 1, pp. 251–261, Apr. 2006.

[192] D. C. Plaut, "Graded modality-specific specialisation in semantics: A computational account of optic aphasia," *Cognit. Neuropsychol.*, vol. 19, no. 7, pp. 603–639, Oct. 2002.

[193] B. A. Wandell, A. A. Brewer, and R. F. Dougherty, "Visual field map clusters in human cortex," *Phil. Trans. Roy. Soc. B, Biol. Sci.*, vol. 360, no. 1456, pp. 693–707, Apr. 2005.

[194] K. Uludağ, J. Steinbrink, A. Villringer, and H. Obrig, "Separability and cross talk: Optimizing dual wavelength combinations for near-infrared spectroscopy of the adult head," *NeuroImage*, vol. 22, no. 2, pp. 583–589, Jun. 2004.

[195] R. J. Janse, T. Hoekstra, K. J. Jager, C. Zoccali, G. Tripepi, F. W. Dekker, and M. van Diepen, "Conducting correlation analysis: Important limitations and pitfalls," *Clin. Kidney J.*, vol. 14, no. 11, pp. 2332–2337, Nov. 2021.

[196] A. Kassab, J. Le Lan, P. Vannasing, and M. Sawan, "Functional near-infrared spectroscopy caps for brain activity monitoring: A review," *Appl. Opt.*, vol. 54, no. 3, pp. 576–586, 2015.

[197] T. Yamada, S. Umeyama, and M. Ohashi, "Removal of motion artifacts originating from optode fluctuations during functional near-infrared spectroscopy measurements," *Biomed. Opt. Exp.*, vol. 6, no. 12, pp. 4632–4649, 2015.

[198] R. A. Khan, N. Naseer, N. K. Qureshi, F. M. Noori, H. Nazeer, and M. U. Khan, "fNIRS-based neurorobotic interface for gait rehabilitation," *J. NeuroEng. Rehabil.*, vol. 15, no. 1, pp. 1–17, Dec. 2018.

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