REVIEW ARTICLE

TRENDS in
Sport Sciences
2021; 28(**2**): 93-107
ISSN 2299-9590
DOI: 10.23829/TSS.2021.28.2-3

Evaluation of cerebral cortex activation during balance tasks using fNIRS: a systematic review

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Abstract

Introduction. Functional near-infrared spectroscopy (fNIRS) is used as a neuroimaging tool for the study of different areas of the brain involved in motor control through the measurement of changes in brain hemodynamics. Its wireless usage and portability has made it suitable for investigating the cortical control of postural balance under static and dynamic testing conditions. Aim of Study. The aim of this systematic review is to evaluate studies on cortical activation while performing static and dynamic balance tasks using fNIRS as a tool and emphasizing the location of brain areas activated. Material and Methods. The search was performed following the PRISMA guidelines. Relevant keywords were used for the search through Google Scholar, PubMed, Science Direct, Taylor and Francis, and Scopus. The methodological quality of included studies was assessed using the Downs and Black checklist. Ten studies met the inclusion criteria. Results. The included studies were found to be of good methodological quality. The results in this review showed that the dorsolateral prefrontal cortex, sensory motor area and superior temporal gyrus are activated predominantly during static and dynamic balance tasks. Conclusions. The recent findings reflect a whole new scope of analysis involving multitasking during complex motor activities. The fNIRS technique is an adjunct to assess static and dynamic postural imbalances in persons with balance related issues with availability of a greater number of channels and more regions of interest to be covered at one given instance.

KEYWORDS: balance, static balance, dynamic balance, cortical activation, neuroimaging, wireless fNIRS.

Received: 21 December 2020
Accepted: 3 February 2021

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Introduction

Balance is defined as the ability to maintain the body's centre of gravity over its base of support with minimal sway and maximal steadiness [11, 30], and it is a key component of motor skills ranging from maintaining posture to executing complex motor skills. When equilibrium is maintained during stationary activity it is termed as static balance, while maintaining equilibrium during motion is termed as dynamic balance [35]. It requires integrating sensory information from the visual, vestibular and somatosensory system [8] and it is a vital component of the human body to function optimally and stay injury free [12]. This component is a determinant of appropriate biomechanics [20], which is helpful in freedom of movements and maintenance of quality of life [22, 23]. Balance abilities can be tested with a functional approach to check for existing balance problems and to assess the risk of falling as well. The importance of various centers such as the primary motor cortex, premotor cortex, supplementary motor area, prefrontal cortex (PFC) and their role in postural control is of great importance as any alteration in the functioning of these structures leads to altered biomechanics of an individual [22, 23, 34].

Functional near-infrared spectroscopy (fNIRS) is used as a neuroimaging tool for the study of different areas of the brain involved in motor control through the measurement of changes in brain hemodynamics [5].

Neuroimaging studies have focused on investigation of brain activation during maintenance of standing posture control [21, 26, 31]. fNIRS is one of the functional neuroimaging techniques, which detects differences in the absorption spectra of oxygenated hemoglobin (Oxy Hb) versus deoxygenated hemoglobin (Deoxy Hb) in the near-infrared spectrum range of 700-900 nanometers. Advantages of fNIRS compared to other neuroimaging techniques such as functional magnetic resonance imaging (fMRI), positron emission technique (PET) or electroencephalogram (EEG) include its non-invasiveness, good spatial (≈1.0-3.0 cm) and temporal resolution (normally up to 10 Hz), robustness against artifacts and lately its wireless usage and portability. This has made it suitable for investigating the cortical control of postural balance under static and dynamic testing conditions [9].

Among various techniques, e.g. fMRI, PET, and EEG, have certain limitations for the analysis of movement control strategies, exercise-cognition experiments have not been extensively done [9, 29]. fMRI is immobile, susceptible to movement artifacts and has a relatively low temporal resolution [19]. PET is expensive and since it uses radioactive tracer substances it is not suitable for experiments involving repetitive testing [28]. Similarly, EEG is susceptible to movement artifacts and it is a time-consuming process [3]. Previous studies did use PET [2, 26] and EEG [1, 4, 33], but they focused on restricted static balance control paradigms and this limits the number of balance challenge tasks that can be evaluated. This stationary characteristic of these neuroimaging technologies prevented us from assessing full mobility and restricted our understanding of neural mechanisms essential for balance control under various scenarios.

A previous systematic review [34] on cortical imaging of human balance control studies included fNIRS, EEG and fMRI. Pertaining to fNIRS they reported 21 studies, out of which only 2 studies were based on wireless fNIRS technology. As technological advancements have taken place it has enabled researchers to study static as well as dynamic balance and their associated cortical activation patterns with the use of wireless fNIRS. Thus, this systematic review was designed to evaluate studies on cortical activation while performing static and dynamic balance tasks using fNIRS as a tool and to focus on different locations of brain areas activated in static and dynamic tasks.

Material and Methods

Search strategy

This systematic review used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Figure 1) approaches [17]. The keywords included fNIRS, balance, human balance, static balance control, dynamic balance control, brain activation during balance, postural balance and equilibrium. These search keywords were linked with "AND" to ensure that at least one term of each field could be found in the results. The terms in each of the search fields were linked with "OR". The articles published between the year 2000-2020 were included.

Search process

The primary information sources included in this review are: Google Scholar, PubMed, Science Direct, Taylor and Francis, and Scopus. The database search included search terms found in the article title, abstracts and keywords. The results from each database were added to the Zotero software and checked for any duplicate results.

Inclusion and exclusion criteria

Search inclusion and exclusion were based on the use of fNIRS neuroimaging modality. Literature included in this review aimed to investigate human balance control using fNIRS. Studies were included if their task incorporated balance challenges (e.g. perturbations, eyes closed, dual-task, balance testing equipment, etc.). Only articles in the English language were considered.

We excluded literature from this review when either the neuroimaging technique was other than fNIRS and balance testing involved walking balance or any other method which did not match the goals of the study. We also excluded studies involving any neurodegenerative conditions, in which balance was assessed. Studies which used isolated joint movement and coordinated body movement (arms and legs) were excluded.

Data extraction

Three authors (SS; AS; PKS) were involved in the selection of articles independently. All the duplicate articles were removed. All the titles and abstracts were evaluated to exclude unrelated articles. Full texts of all the related articles were examined according to inclusion and exclusion criteria. Information regarding the age of the participants, population characteristics, and areas involved during different balance tasks, region of interest in fNIRS, number of channels used in fNIRS, variables studied (Oxy, Deoxy, differential, total hemoglobin, etc.) task/test involved, data representation, filters used for data refining, company of fNIRS were assessed in the studies.

Methodological quality assessment

Each included study was assessed for quality using the Downs and Black checklist [6]. This checklist includes

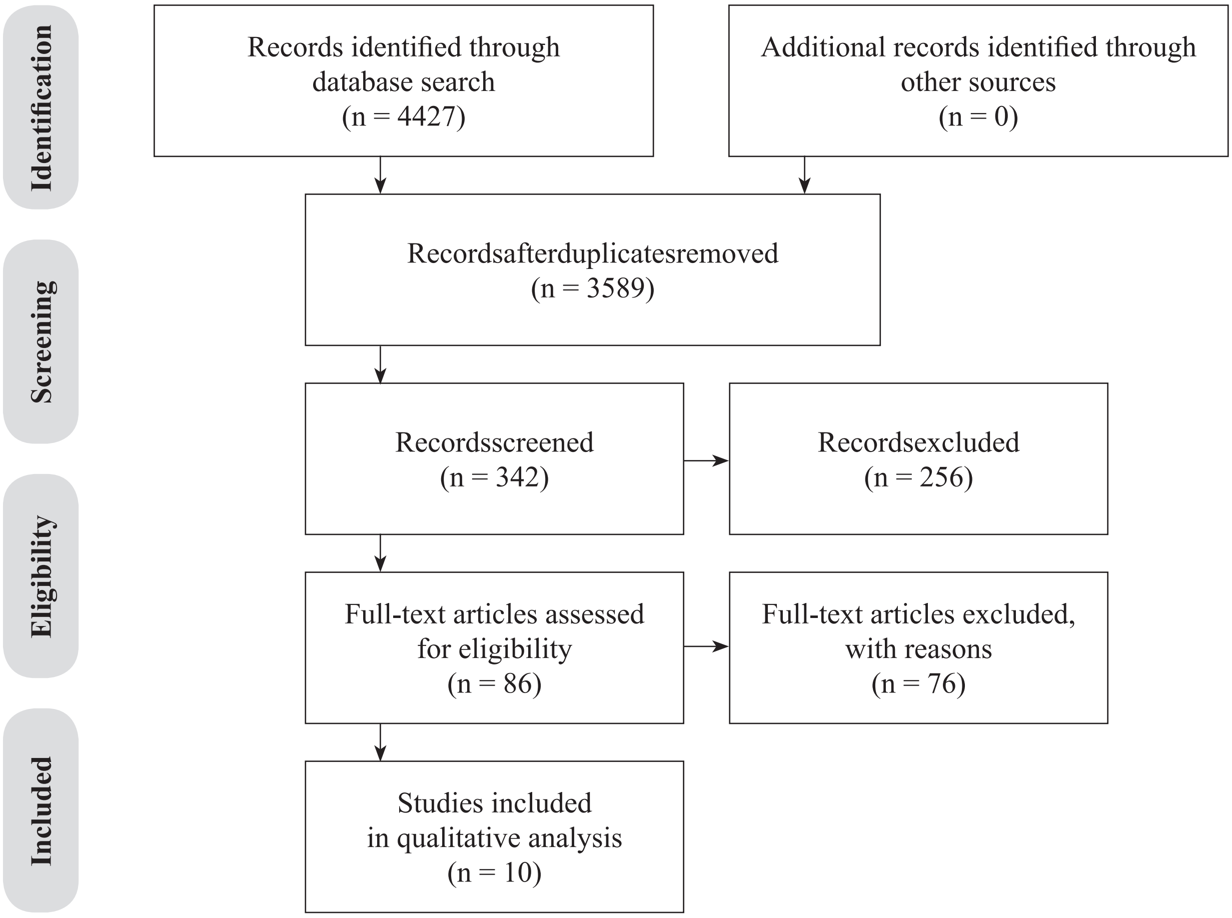

Figure 1. PRISMA flow chart of search strategy and retrieval of articles

27 criteria, covering areas of reporting quality, external and internal validity, and power. The quality of each study was independently assessed by the three authors, with discrepancies resolved through discussion and agreement.

Results

The database search and additional sources yielded 4427 records (Figure 1). After the removal of duplicates and records with missing/unavailable abstracts, 3589 records remained. After screening of relevant articles 342 remained, after which the relevancy of the topic, availability of full article, as well as full text eligibility were checked. The number of articles included in the final synthesis was 10 (n = 10). Reasons for exclusion during the full-text eligibility assessment were the following: a large number of studies were outside the scope of our aim of use of the fNIRS neuroimaging technique and balance tasks. The qualitative analysis (Table 1) was carried out as per the Downs and Black, 1998 [6]. All extracted relevant information of the articles selected for final synthesis is shown in Tables 2, 3 and 4. The inclusion criteria were taken into account.

Quality assessment

According to the quality assessment scale by Downs and Black, 1998 [6], the corresponding quality levels as stated are scores of excellent (26-28), good (20-25), fair (15-19) and poor quality (≤14). We found that out of the 10 included studies, all were of good quality according to the criteria in the scale. Four studies had a score of 20 and five studies had a score of 21, while one study had a score of 22 details, which is represented in Table 1.

Characteristics of subjects

All the included participants in the studies were healthy adults. Out of the 10 studies analysed, eight studies included only young adults, one study [32] had younger and older adult subjects and one study [18] had middle-aged and old-aged subjects. The mean age (in years) for

Table 1. Downs and Black checklist for quality assessment of included fNIRS studies

		Mihara et al., 2008 [21]	Karim et al., 2012 [14]	Karim et al., 2013 [13]	Moro et al., 2014 [24]	Ferrari et al., 2014 [7]	Hiyamizu et al., 2014 [10]	Takakura et al., 2015 [31]	Herold et al., 2017 [8]	Lin et al., 2017 [18]	Teo et al., 2018 [32]
REPORTING											
Q1.	Hypothesis / aim / objective clearly described	1	1	1	1	1	1	1	1	1	1
Q2.	Main outcomes in Introduction or Methods	1	1	1	1	1	1	1	1	1	1
Q3.	Patient characteristics clearly described	1	1	1	1	1	1	1	1	1	1
Q4.	Interventions of interest clearly described	1	1	1	1	1	1	1	1	1	1
Q5.	Principal confounders clearly described	1	1	1	1	1	1	1	1	1	1
Q6.	Main findings clearly described	1	1	1	1	1	1	1	1	1	1
Q7.	Estimates for random variability provided for main outcomes	0	0	1	1	1	1	1	1	1	1
Q8.	All adverse events of intervention reported	1	1	1	1	1	1	1	1	1	1
Q9.	Characteristics of patients lost to follow-up described	1	1	1	1	1	1	1	1	1	1
Q10.	Probability values reported for main outcomes	1	1	1	1	1	1	1	1	1	1
EXTERNAL VALIDITY											
Q11.	Subjects asked to participate were representative of source population	UTD	UTD	UTD	UTD	UTD	0	UTD	UTD	UTD	UTD
Q12.	Subjects prepared to participate were representative of source population	1	1	1	1	1	1	1	1	1	1
Q13.	Location and delivery of study treatment was representative of source population	1	1	1	1	1	1	1	1	1	1
INTERANAL VALIDITY – BIAS AND CONFOUNDING											
Q14.	Study participants blinded to treatment	UTD	UTD	UTD	UTD	UTD	0	UTD	0	UTD	UTD
Q15.	Blinded outcome assessment	UTD	UTD	UTD	UTD	UTD	0	UTD	UTD	UTD	UTD
Q16.	Any data dredging clearly described	1	0	0	0	0	1	1	1	1	1
Q17.	Analyses adjust for differing lengths of follow-up	1	1	1	1	1	1	1	1	1	1
Q18.	Appropriate statistical tests performed	1	1	1	1	1	1	1	1	1	1
Q19.	Compliance with interventions was reliable	1	1	1	1	1	1	1	1	1	1
Q20.	Outcome measures were reliable and valid	1	1	1	1	1	1	1	1	1	1
Q21.	All participants recruited from the same source population	1	1	1	1	1	1	1	1	1	1

Q22.	All participants recruited over the same time period	1	1	1	1	1	1	1	1	1	1
Q23.	Participants randomized to treatment(s)	UTD	UTD	UTD	UTD	UTD	1	UTD	UTD	UTD	UTD
Q24.	Allocation of treatment concealed from investigators and participants	UTD	UTD	UTD	UTD	UTD	0	UTD	UTD	UTD	UTD
Q25.	Adequate adjustment for confounding	1	1	1	1	1	0	1	1	1	1
Q26.	Losses to follow-up taken into account	1	1	1	1	1	1	1	1	1	1
POWER											
Q27.	Sufficient power to detect treatment effect at significance level of 0.05	0	1	1	0	0	0	1	0	0	1
TOTAL		20	20	21	20	20	21	21	21	21	22
		GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD

Note: 0 = NO; 1 = YES; UTD = unable to determine. Downs and Black score ranges were given corresponding quality levels [6]: excellent (26-28); good (20-25); fair (15-19); and poor (≤14)

Table 2. Illustration of included fNIRS studies

Sr. No.	Author	Aim	Population	Procedure	Regions of interest	Variables focused
1.	Mihara et al., 2008 [21]	To evaluate perturbation based changes in the prefrontal cortex.	15 healthy subjects (9 males, 6 females)	Two conditions: warned and unwarned were tested; an auditory warning signal was provided 2 sec before perturbation in the former condition, while it was not provided in the latter condition. Before each measurement was started, the current condition was informed to the subjects. In each condition, 20-30 perturbations were provided at intervals randomized between 5 and 20 sec (mean, 10 sec). Perturbation was provided as a horizontal translation of a custom-made moving platform. The subjects were instructed to stand at the center of the platform with their feet shoulder-width apart.	bilateral frontal and parietal cortices	Oxy Hb Deoxy Hb
2.	Karim et al., 2012 [14]	To record blood flow changes in the frontal, motor, sensory, and temporal cortices during active balancing associated with playing a video game simulating downhill skiing (Nintendo WiiTM; Wii-FitTM).	9 healthy subjects (5 males, 4 females)	The test method included repeated trials of a commercial video game simulating downhill slalom skiing (Nintendo Wii$^{\text{TM}}$; Wii-Fit$^{\text{TM}}$ video game). Each subject preformed 6 trials at the beginner level and 8 trials at the advanced level. Participants stood on an instrumented balance board for 30 sec (standing rest), after which the game was started. A 30-sec standing rest period was added after the subject reached the bottom of the virtual ski slope. The balance task (skiing down the hill) was self-paced depending on the skill and speed of the subject.	bilateral prefrontal cortex, frontal cortex, and superior temporal gyrus	Oxy Hb Deoxy Hb
3.	Karim et al., 2013 [13]	To investigate how the brain processes information from multiple sensory modalities during dynamic posturography.	15 healthy subjects (9 males, 6 females)	The method included posturography while undergoing fNIRS brain imaging. Four standard conditions from the sensory organization test (SOT) were performed and each consisted of an initial baseline condition (45 sec), a test condition (45 sec), and a repeat of the baseline condition (60 sec). Each condition challenged one sensory condition when going from baseline to test condition while the other was kept constant. For e.g. if the baseline was vestibular proprioception then vestibular was tested.	bilateral frontal, temporal and parietal brain regions	Oxy Hb Deoxy Hb
4.	Moro et al., 2014 [24]	To assess prefrontal cortex oxygenation response during an incremental and a control swing balance task (ISBT and CSBT, respectively) in a semi-immersive virtual reality (VR) environment driven by a depth-sensing camera.	16 healthy male subjects	Subjects were asked to stand barefoot while watching a 3D virtual representation of themselves projected onto a screen. They had to maintain their balance on a virtual blue swing board susceptible to external destabilizing perturbations during a 3-min ISBT (performed at four levels of difficulty) or during a 3-min CSBT (performed constantly at the lowest level of difficulty of the ISBT). The protocol included the ISBT and the CSBT; each task lasted 7 min. During the first 2 min (baseline), each subject was asked to stand still observing his image and the blue virtual swing board represented on the projection screen by the 3D model followed by an auditory signal indicated the start of a 3-min ISBT or CSBT. The ISBT was divided in four steps (S1; S2; S3; S4) of increasing difficulty (i.e., 1-4 m/s), each 45 sec in duration, and each level of difficulty contained 7 random perturbations (forward backward direction).	prefrontal cortex (Brodmann areas 10, 11 and 46)	Oxy Hb Deoxy Hb

				The CSBT was divided in four steps (S1; S2; S3; S4) of constant difficulty, each 45 sec in duration, executed at the lowest level of difficulty of the ISBT (i.e., 1 m/s). Each step contained 7 random perturbations (forward–backward direction). After the end of the last step of ISBT/CSBT, each subject had to observe his image on the projection screen without moving his body for 2 min (recovery time). The interval between the two tasks was 3 min, and the task order was counterbalanced across subjects.		
5.	Ferrari et al., 2014 [7]	To assess by fNIRS the prefrontal cortex oxygenation response to a tilt board balance task, performed either at constant (control tilt board balance task – CTBBT) or incremental (incremental tilt board balance task – ITBBT) level of difficulty executed in a semi-immersive virtual reality environment driven by a depth-sensing camera.	22 healthy male subjects	The task involved medial–lateral postural sways on a virtual tilt board (VTB) balancing over a pivot. The protocol included ITBBT and CTBBT; each lasted 9 min. Twenty two subjects were divided into two groups performing ITBBT and CTBBT, respectively. During the first 2-min (baseline), the subject was asked to stand still observing his image (represented on the screen by the 3D model). The 5-min ITBBT or CTBBT was started by a beep.	bilateral prefrontal cortex	Oxy Hb Deoxy Hb
6.	Hiyamizu et al., 2014 [10]	To compare effects of observing the performance of others and self-performance on standing balance learning in healthy young subjects and to examine cortical activation during performance using functional near-infrared spectroscopy (fNIRS).	39 healthy young subjects (24 females, 15 males); groups consisting of an equal number of 13 subjects (8 females and 5 males per group): Control, Other Observation (OO), and Self-Observation (SO) group	All subjects were instructed to keep the platform horizontal for 30 sec after a preparation period of sitting on a high chair for 30 sec. A rest period with sitting for 30 sec after the task was given. All subjects performed 5 practice trials following a pre-test and then performed a post-test. Additionally, they performed a retention test at 24 h after the post-test. All subjects were instructed to look at a target placed 2 m in front of the subject at eye level during task performance, and they were permitted to use their upper extremities to maintain balance.	supplementary motor area (SMA), premotor cortex (PMC), and dorsolateral prefrontal cortex (DLPFC)	Oxy Hb Deoxy Hb Total Hb

7.	Takakura et al., 2015 [31]	To investigate cortical cognitive processes during instances of sensory conflict in postural balance activities.	11 healthy male subjects	Each subject performed the EquiTest® SOT (NeuroCom International, Inc., USA), which is an objective assessment of the main sensory systems involved in balance and stability. Each subject completed 5 trials under each condition. Each trial lasted 20 sec and each trial interval was set for more than 60 sec. During the trial, each subject stood on a fixed platform with his eyes open and with the three sensory systems operational (i.e., under the same conditions as SOT 1). After completing 3 trials under the six SOT conditions, the subjects rested for a few minutes. This task involved 30 trials overall and typically lasted about 60 min. The six sensory conditions were analyzed to find the involvement of vision, vestibular and somatosensory inputs in the balance function.	right frontal operculum/inferior frontal gyrus (f-Op), right parietal operculum (p-Op), frontal eye field (FEF), right supramarginal gyrus, right angular gyrus, right superior temporal gyrus (STG), lateral part of sensorimotor cortex in the right hemisphere, medial part of the sensorimotor cortex, superior parietal lobule, and the supplementary motor area	Oxy Hb
8.	Herold zet al., 2017 [8]	To evaluate the effect of balancing on a balance board on cortical activity in sensorimotor areas as assessed by fNIRS and to identify possible relations between sway parameters and hemodynamic responses in sensorimotor brain areas.	10 healthy young adult subjects	fNIRS and balance board (TOGU Board Tri axial inertial measurement unit) was used in the testing method. Every participant performed three blocks, in which a block consisted of three phases: at first participants had to stand still on the floor for 30 sec (baseline) and then another 30 sec for the standing condition. Afterwards, they stepped on the balance board and maintained balance in feet side by side position for 30 sec (balance condition). After each balancing period they had to step down and were allowed to rest standing on the floor for 30 sec.	supplementary motor area (SMA), precentral gyrus, postcentral gyrus	Oxy Hb Deoxy Hb
9.	Lin et al., 2017 [18]	To investigate hemodynamic changes in frontal-lateral, temporal-parietal, and occipital regions of interest (ROIs) during four sensory integration conditions that manipulate visual and somatosensory feedback.	15 middle-aged subjects (5 males, 10 females) and 15 older adults subjects (8 males, 7 females)	All participants performed 4 trials of standing on a NeuroCom posturography platform (Natus®, USA). The sensory modifications involved changing either visual input [eyes open in light (EO) and dark (EOD)] or somatosensory input [fixed or sway-referenced (SR) platform]. The EOD condition was accomplished by having the participants keep their eyes open while wearing darkened goggles. Each trial consisted of a change from greater sensory input to reduced sensory input. Each subblock lasted 40 sec. All participants performed the four trials one time, in a random order.	five ROIs; occipital, right frontal lateral, right temporal parietal, left frontal lateral, left temporal parietal	Oxy Hb Deoxy Hb

10.	Teo et al., 2018 [32]	To investigate the effects of aging on the dorsolateral prefrontal cortex when sensory cues are removed or presented inaccurately (i.e. increased sensory complexity) during the sensory orientation test (SOT).	20 young subjects (aged 18-25 years, 10 males, 10 females) and 18 older (aged 66-73 years, 10 males, 8 females) sedentary, otherwise healthy adult subjects	The NeuroCom Balance Master system (NeuroCom International Inc, USA) was used for SOT, which comprised six different sensory conditions in quiet stance, and measured the center of pressure (COP) path. The test started with condition 1 (eyes open in a static stance), and consecutively moved through each condition which progressively became more challenging by either distracting or removing visual and/or proprioceptive feedback. The visual surround and force platform were sway-referenced, which referred to the tilting of the support surface and/or visual surround in response to movement of the participant's COP. Three 20-sec trials were conducted for each sensory condition with an inter trial rest period of 60 sec. During each rest period, all participants were allowed to adjust their foot position if needed and were asked to remain standing still upright for at least 30 sec with their eyes opened and focused onto a fixation cross at eye-level in front.	bilateral dorsolateral prefrontal cortex (DLPFC)	Oxy Hb Deoxy Hb

Table 3. Cortical activation location of included fNIRS studies

Sr. No.	Author	Type of balance task	Cortical activation areas
1.	Mihara et al., 2008 [21]	static	Enhanced activation in the sensory motor area and right posterior parietal cortex was observed. Significant task-related increase of Oxy Hb signals after postural perturbation. No significant signal changes in Deoxy Hb were reported. In the frontal cortices, the left and right middle frontal gyri, the left and right superior frontal gyri, the left supplementary motor area, and the left precentral gyrus showed significant task-related increase of Oxy Hb signals after postural perturbation. In the parietal cortices, the left postcentral gyrus, the left and right superior parietal lobules also showed a significant task-related increase of Oxy Hb signals.
2.	Karim et al., 2012 [14]	dynamic	Activation of right superior temporal gyrus was modulated by the difficulty of the task and supramarginal gyrus in both left and right hemispheres.
3.	Karim et al., 2013 [13]	static	Increased activation was reported in the temporo-parietal regions in the area around the superior temporal gyrus, when subjects relied primarily on vestibular information. In the condition when only proprioception was degraded, less activation in the left superior temporal gyrus was observed. When only vision was degraded, a decrease in oxy-hemoglobin in the right prefrontal cortex and left temporoparietal area was observed as well as small activations in the right temporoparietal area. The superior temporal gyrus on either side was found to be activated.
4.	Moro et al., 2014 [24]	dynamic	Oxygenation increased over the prefrontal cortex of both hemispheres in healthy subjects performing an ISBT in a semi-immersive VR environment. The observed prefrontal cortex (PFC) activation was modulated by levels of difficulty of the task signifying that PFC is bilaterally involved in attention-demanding balance tasks. The increase in difficulty during the first three levels led to an increase in Oxy Hb values and a less consistent Deoxy Hb decreased over 8 measurement points of PFC.
5.	Ferrari et al., 2014 [7]	dynamic	The prefrontal cortex (PFC) oxygenation increased in case of subjects performing an ITBBT in a semi-immersive virtual reality environment. The activation increased as the level of difficulty of task suggesting that PFC is bilaterally involved in attention-demanding balance tasks.
6.	Hiyamizu et al., 2014 [10]	static	There was no significant difference in any cortical area in the control and observation groups. Predominantly, in the observation group, SMA and Right DLPFC hemodynamic values remained unchanged post-test. In the self-observation group, post-test values in left DLPFC were significantly decreased compared with the pre-test.
7.	Takakura et al., 2015 [31]	static	Oxy Hb concentrations in the frontal operculum/inferior frontal gyrus (f-Op), right parietal operculum (p-Op), and superior temporal gyrus (STG) around the Sylvian fissure were increased under SOT 2, 3, 5, and 6, and specifically in under SOT 5 and 6. These Oxy Hb and Total Hb responses were gradually decreased after the end of the task. Substantial hemodynamic responses were not observed in any of the region of interest under SOT 1.
8.	Herold et al., 2017 [8]	dynamic	The Oxy Hb values increased considerably from standing to balancing in supplementary motor area (SMA). The analysis of Deoxy Hb values revealed no significant differences between the conditions.
9.	Lin et al., 2017 [18]	static	The temporal-parietal ROI were activated more when somatosensory and visual information was absent in both groups, which indicated the use of vestibular input for maintaining balance. While both older adults and middle-aged adults had greater activity in most brain ROIs during changes in the sensory conditions, older adults had greater increases in occipital ROI and frontal lateral ROIs.
10.	Teo et al., 2018 [32]	static	Bilateral DLPFC activation during postural control increased. The results confirmed that with comparison to younger adults, older adults had greater bilateral DLPFC activation particularly during more complex balance tasks, while younger adults showed greater lateralization to right DLPFC with increased sensory demands.

Note: Oxy Hb – oxygenated hemoglobin; Deoxy Hb – deoxygenated hemoglobin; Total Hb – total hemoglobin

Table 4. fNIRS system characteristics and signal processing methods of included fNIRS studies

Sr. No.	Study	No. of channels used	Filters used	Sampling frequency	Representation of data	Company
1.	Mihara et al., 2008 [21]	50	high pass filter (0.05 Hz)	4 Hz	time line analysis graph	OMM 3000; Shimadzu Corp., Kyoto, Japan
2.	Karim et al., 2012 [14]	32	not mentioned	4 Hz	time line analysis graph brain map	CW6 real time system; TechEn Inc., Milford, Massachusetts, USA
3.	Karim et al., 2013 [13]	32	not mentioned	4 Hz	time line analysis graph	CW6 real time system; TechEn Inc., Milford, Massachusetts, USA
4.	Moro et al., 2014 [24]	8	low pass filter (0.1 Hz)	1 Hz	bar graph box plots graph	NIRO-200, Hamamatsu Photonics, Japan
5.	Ferrari et al., 2014 [7]	8	low pass filter (0.1 Hz)	1 Hz	time line analysis graph	NIRO-200, Hamamatsu Photonics, Japan
6.	Hiyamizu et al., 2014 [10]	51	not mentioned	5 Hz	bar graph	FOIRE-3000; Shimadzu Corp., Kyoto, Japan
7.	Takakura et al., 2015 [31]	50	band-pass Fourier filter (0.01-0.1 Hz)	not mentioned	time line analysis graph bar graph connectivity maps cortical representations maps	OMM 3000; Shimadzu Corp., Kyoto, Japan
8.	Herold et al., 2017 [8]	24	low pass filter (0.5 Hz) and high pass filter (0.01 Hz)	10 Hz	scatter plot graph	Continuous fNIRS Wave System, ETG 4000 optical system, Hitachi Medical Corp., Tokyo, Japan
9.	Lin et al., 2017 [18]	30	not mentioned	4 Hz	bar graph cortical representation maps	CW6 real time system; TechEn Inc., Milford, Massachusetts, USA
10.	Teo et al., 2018 [32]	8	high-pass-0.01 Hz and low-pass-0.50 Hz	10 Hz	bar graph scatter plot graph	OxyMon Mk III, Artinis Medical Systems, The Netherlands

young adults was found to be 25.83±4.60; for middle aged 46±11 and for old aged 71±2.82.

Discussion

The aim of this systematic review was to classify and focus on studies using fNIRS as a tool to investigate the location of activation in the cerebral cortex during the performance of different balance tasks.

Ten studies which met the inclusion criteria were reviewed and further illustrated in the next section and Tables 2, 3 and 4. The balance tasks used in these studies ranged from basic tasks, such as sensory organization test, perturbations and posturography, to more advanced tasks, such as incremental swing balance tasks and downhill skiing on a video game.

Overview of test methods used

fNIRS can be utilized to evaluate changes in cortical activation in a variety of balance tasks. In the studies which met the inclusion criteria for the systematic review (Table 2); four studies used sensory organization balance/posturography test methods to assess balance. Two studies used advance technological instruments, such as the TOGU Board Tri axial inertial measurement unit and tilt board with Noraxon pressure sensors, while one study used a video game (Nintendo WiiTM) in order to challenge the balance of the subjects.

The TOGU Board uses four air-filled balls below the wooden board, which enables people of any fitness level and age to step into sensory motor function training and increase their capabilities. The tilt board with Noraxon pressure sensors enables to record the pressure beneath the foot with an even distribution. The Nintendo WiiTM provides an interactive user interface for testing static and dynamic conditions with the use of pre-installed games.

Overview of fNIRS variables

In the studies included for the systematic review (Table 3), eight studies used both oxy- and deoxyhemoglobin to describe changes in cortical activation, whereas one study used only oxyhemoglobin [31] and one study [10] used oxy, deoxy and total hemoglobin to describe cortical activation. The studies included in this review tend to be focused on one common finding that the oxyhemoglobin (O_2Hb) is mainly linked to the oxygen inflow of the tissue, while deoxyhemoglobin (HHb) is linked to the amount of oxygen absorbed by the tissue. An increase in the O_2Hb is correlated to a decrease in HHb. During activation of the tissue (e.g. excitation of brain areas or straining of muscles), oxygen is consumed within the tissue and hemodynamically the tissue responds by increasing the flow of blood toward that tissue. Combining both O_2Hb and HHb yields the total hemoglobin concentration changes, which are linked to changes in total blood volume in the tissue underneath the sensor [9].

Usage of channels for assessing cortical activation changes in the studies included for the systematic review were as follows;three studies [7, 24, 32] used 8 channels, two studies [13, 14] used 32 channels, two studies used 50 channels [21, 31], one study [10] used 51 channels, one study [18] used 30 channels and one study [8] used 24 channels.

Signal acquisition in fNIRS requires a set frequency and filtering techniques to remove artifacts. Physiological noises such as heartbeat, respiration, blood pressure fluctuations, extra-cortical noises from the superficial layers, and motion artifacts affect the obtained cortical activity data [34]. It is essential to remove these noises prior to analyzing the brain functions.

Overview of signal processing of fNIRS data

In preprocessing of the fNIRS data, the physiological noises are removed using band pass filtering [15, 27] with cut-off frequencies of approximately 0.01-0.9 Hz that corrects the artifacts in the frequency range between a low pass and high pass filter [16, 25, 27]. The review included:four studies [13, 14, 18, 21] using 4 Hz, two studies [8, 32] using 2 Hz, two studies [7, 24] using 1 Hz and one study [10] using 5 Hz as their sampling frequency. The filters used were band pass filters in three studies [8, 21, 31]; low pass filters in two studies [7, 24], while one study [21] reported the use of high pass filters for refining the data. As per the technological availability the pre-processing and removal of movement artifacts was done in the included studies.

Overview of cortical activation

This study reviewed 10 articles using fNIRS neuroimaging modality to investigate the cortical activation involved in human balance control. This review reported that different tasks elicited different areas of brain activation. The dorsolateral prefrontal cortex was activated during postural control tasks, which were attention demanding [7, 10, 18, 24, 32]. There was activation of the sensory motor area (SMA) observed in four studies, which met the inclusion criteria. In their study Hiyamizu et al., 2014 [10], when studying changes during balance learning reported that there was an increase in Oxy Hb in SMA post training of a previously learned task of balance. Herold et al., 2017 [8] stated that Oxy Hb increased in SMA more during a balance task as compared to standing, emphasizing the use of higher cortical processes. The investigated studies show that SMA activation is dependent on the level of difficulty imposed during the balance task.

Mihara et al., 2008 [21] studied changes in SMA during two conditions of perturbation; warned and unwarned, in which they reported a significant activation in the case of warned perturbation because of preparation to an impending activity, which was not found in the case of an unwarned situation. They also reported that the posterior parietal cortex got activated due to warned and unwarned perturbations as a preparation to the forthcoming perturbation involving visuospatial attention.

Takakura et al., 2015 [31] reported a significant increase in Oxy Hb and Total Hb of SMA in stages 5 and 6 of the sensory organization test (total 6 stages), as these stages compromise more sensory inputs. However, no significant difference was reported from the baseline in the values of the initial stages. It was also found that the posterior parietal cortex was activated during a task involving obstruction of vestibular and visual information. The results prove that the supplementary motor area is involved in the execution of volitional action and establishment of new motor programs to maintain postural balance. The posterior parietal cortex and the premotor cortex are involved in the updating and computation of spatial reference frames during instances of a sensory conflict between vestibular and visual information.

Karim et al., 2013 [13] reported that the superior temporal gyrus (STG) became activated during the sensory organization test when subjects relied primarily on vestibular information. In a situation when only proprioception was degraded, less activation in the left superior temporal gyrus was observed. Compared to when only vision was degraded, a decrease was observed in oxyhemoglobin in the right prefrontal cortex and left temporo-parietal area, as well as small activations in the right temporo-parietal area. The superior temporal gyrus on either side was found to be activated. In another study [14], which involved a downhill slalom skiing video game task it was found that the activation of the right superior temporal gyrus was observed as an adjustment to the increased difficulty of the video game task involving inclination and also thesupramarginal gyrus in both the left and right hemispheres.

These findings provide insight into how the visual, somatosensory, auditory and vestibular systems are in conjunction to each other for maintaining an individual's balance. Moreover, the included literature confirmed the use of fNIRS as a neuro-imaging technique to analyze brain activation during static and dynamic balance tasks as an advantage over fMRI, EEG and PET scan where the movement must be restricted.

There are few limitations of fNIRS including inability to assess deeper structures of the brain [9]. Studies included [7, 24, 32] had the limitation with regard to the availability of usage of channels. Another limitation was the area to be tested at one given instance, such as reported by [13, 14], who were not able to examine the occipital lobe due to technical limitations.

Practical relevance

The relatively recent breakthroughs in wireless neuroimaging have empowered researchers to examine brain function during normal human movement. It is obvious that the use of neuroimaging systems to the domain of human balance control is still developing. Significant opportunities remain in the detection of neural mechanisms underlying the control of human balance and the use of these structures should be completely portable and should be able to assess functional limitations as incurring in our daily lives.

Future directions

Larger areas and a greater number of channels must be used in future studies in order to show a clear picture of cortical activation during balanced tasks. Both static and dynamic tasks need to be used in a particular study and must be compared for cortical activation. The effect of confounding variables such as age, gender, physical activity levels and regular sporting activity might be addressed further.

Conclusions

The results of this review showed that the bilateral dorsolateral prefrontal cortex, sensory motor area predominantly get activated during both static and dynamic balance tasks. Specifically in the case of dynamic balance tasks the right superior temporal gyrus becomes activated, whereas during static balance tasks cortical areas of the frontal operculum, right patietal operculum, temporo-parietal cortex and bilateral superior temporal gyurus get activated. With developments in fNIRS a whole new dimension of brain activity and cognition has opened up because of the unique advantages of this technology, which facilitates quantification of brain activity during the execution of various movements and tasks. This technique serves as an adjunct to assess static and dynamic postural imbalances in persons with balance related issues with a greater number of channels and more regions of interest to be covered at one given instance.

Conflict of interests

The authors declare no conflict of interest.

References

1. Adkin AL, Quant S, Maki BE, McIlroy WE. Cortical responses associated with predictable and unpredictable compensatory balance reactions. Exp Brain Res. 2006 Jun;172(1):85-93.
2. Cham R, Perera S, Studenski SA, Bohnen NI. Striatal dopamine denervation and sensory integration for balance in middle-aged and older adults. Gait Posture. 2007 Oct;26(4):516-525.
3. Cohen MX. Where does EEG come from and what does it mean? Trends Neurosci. 2017;40(4):208-218.
4. Collado-Mateo D, Adsuar JC, Olivares PR, Cano-Plasencia R, Gusi N. Using a dry electrode EEG device during balance tasks in healthy young-adult males: Test–retest reliability analysis. Somatosens Mot Res. 2015 Oct 2;32(4):219-226.
5. Doi T, Makizako H, Shimada H, Park H, Tsutsumimoto K, Uemura K, et al. Brain activation during dual-task walking and executive function among older adults with mild cognitive impairment: a fNIRS study. Aging Clin Exp Res. 2013 Oct;25(5):539-544.
6. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. J Epidemiol Community Health. 1998 Jun 1; 52(6):377-384.
7. Ferrari M, Bisconti S, Spezialetti M, Basso Moro S, Di Palo C, Placidi G, et al. Prefrontal cortex activated bilaterally by a tilt board balance task: afunctional near-infrared spectroscopy study in a semi-immersive virtual reality environment. Brain Topogr. 2014 May;27(3):353-365.
8. Herold F, Orlowski K, Börmel S, Müller NG. Cortical activation during balancing on a balance board. Hum Mov Sci. 2017 Jan;51:51-58.
9. Herold F, Wiegel P, Scholkmann F, Müller N. Applications of functional near-infrared spectroscopy (fNIRS) neuroimaging in exercise–cognition science: asystematic, methodology-focused review. J Clin Med. 2018 Nov 22;7(12):466.
10. Hiyamizu M, Maeoka H, Matsuo A, Morioka S. Effects of self-action observation on standing balance learning: a change of brain activity detected using functional near-infrared spectroscopy. NeuroRehabilitation. 2014 Nov 14;35(3):579-585.
11. Horak FB. Clinical measurement of postural control in adults. Phys Ther. 1987 Dec 1;67(12):1881-1885.
12. Hrysomallis C. Relationship between balance ability, training and sports injury risk. Sports Med. 2007;37(6): 547-556.
13. Karim H, Fuhrman SI, Sparto P, Furman J, Huppert T. Functional brain imaging of multi-sensory vestibular processing during computerized dynamic posturography using near-infrared spectroscopy. NeuroImage. 2013 Jul;74:318-325.
14. Karim H, Schmidt B, Dart D, Beluk N, Huppert T. Functional near-infrared spectroscopy (fNIRS) of brain function during active balancing using a video game system. Gait Posture. 2012 Mar 1;35(3):367-372.
15. Khan RA, Naseer N, Qureshi NK, Noori FM, Nazeer H, Khan MU. fNIRS-based Neurorobotic Interface for gait rehabilitation. J Neuroeng Rehabil. 2018;15(7). https://doi.org/10.1186/s12984-018-0346-2.
16. Klein F, Kranczioch C. Signal processing in fNIRS: acase for the removal of systemic activity for single trial data. Front Hum Neurosci. 2019 Sep 24;13: 331.https://doi.org/10.3389/fnhum.2019.00331.
17. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JPA, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. PLoS Med. 2009 Jul 21;6(7):e1000100.
18. Lin C-C, Barker JW, Sparto PJ, Furman JM, Huppert TJ. Functional near-infrared spectroscopy (fNIRS) brain imaging of multi-sensory integration during computerized dynamic posturography in middle-aged and older adults. Exp Brain Res. 2017 Apr;235(4):1247-1256.
19. Lloyd-Fox S, Blasi A, Elwell CE. Illuminating the developing brain: the past, present and future of functional near infrared spectroscopy. Neurosci Biobehav Rev. 2010 Mar;34(3):269-284.
20. Majewski M, Bischoff-Ferrari HA, Grüneberg C, Dick W, Allum JHJ. Improvements in balance after total hip replacement. J Bone Joint Surg Br. 2005 Oct;87-B(10):1337-1343.
21. Mihara M, Miyai I, Hatakenaka M, Kubota K, Sakoda S. Role of the prefrontal cortex in human balance control. NeuroImage. 2008 Nov;43(2):329-336.
22. Morasiewicz P, Dragan S. Pedobarographic evaluation of body weight distribution on the lower limbs and balance after derotation corticotomies using the Ilizarov method. Acta Bioeng Biomech. 2013;15(2):91-96.
23. Morasiewicz P, Konieczny G, Dejnek M, Urbański W, Dragan SŁ, Kulej M, et al. Assessment of the distribution of load on the lower limbs and balance before and after ankle arthrodesis with the Ilizarov method. Sci Rep. 2018

Oct 24;8(1):15693. https://doi.org/10.1038/s41598-018-34016-3.

24. Moro S, Bisconti S, Muthalib M, Spezialetti M, Cutini S, Ferrari M, et al. A semi-immersive virtual reality incremental swing balance task activates prefrontal cortex: a functional near-infrared spectroscopy study. NeuroImage. 2014 Jan;85:451-460.
25. Nguyen T, Babawale O, Kim T, Jo HJ, Liu H, Kim JG. Exploring brain functional connectivity in rest and sleep states: a fNIRS study. Sci Rep. 2018;8(1). https://doi.org/10.1038/s41598-018-33439-2.
26. Ouchi Y, Okada H, Yoshikawa E, Nobezawa S, Futatsubashi M. Brain activation during maintenance of standing postures in humans. Brain J Neurol. 1999 Feb;122 (Pt 2):329-338.
27. Pinti P, Tachtsidis I, Hamilton A, Hirsch J, Aichelburg C, Gilbert S, et al. The present and future use of functional near-infrared spectroscopy (fNIRS) for cognitive neuroscience: advances in using fNIRS in cognitive neuroscience. Ann N Y Acad Sci. 2020 Mar;1464(1):5--29. Epub 2018 Aug 7.
28. Rudroff T, Ketelhut NB, Kindred JH. Metabolic imaging in exercise physiology. J Appl Physiol Bethesda Md 1985. 2018 Feb 1;124(2):497-503.
29. Seraglia B, Gamberini L, Priftis K, Scatturin P, Martinelli M, Cutini S. An exploratory fNIRS study with immersive virtual reality: a new method for technical implementation. Front Hum Neurosci. 2011 Dec 28;5:176.
30. Shumway-Cook A, Anson D, Haller S. Postural sway biofeedback: its effect on reestablishing stance stability in hemiplegic patients. Arch Phys Med Rehabil. 1988 Jun;69(6):395-400.
31. Takakura H, Nishijo H, Ishikawa A, Shojaku H. Cerebral hemodynamic responses during dynamic posturography: analysis with a multichannel near-infrared spectroscopy system. Front Hum Neurosci. 2015 Nov 17;9:620.
32. Teo W-P, Goodwill AM, Hendy AM, Muthalib M, Macpherson H. Sensory manipulation results in increased dorsolateral prefrontal cortex activation during static postural balance in sedentary older adults: an fNIRS study. Brain Behav. 2018 Oct;8(10):e01109.
33. Thompson J, Sebastianelli W, Slobounov S. EEG and postural correlates of mild traumatic brain injury in athletes. Neurosci Lett. 2005 Apr;377(3):158-163.
34. Wittenberg E, Thompson J, Nam CS, Franz JR. Neuroimaging of human balance control: asystematic review. Front Hum Neurosci. 2017 Apr 10;11:170.
35. Yim-Chiplis PK, Talbot LA. Defining and measuring balance in adults. Biol Res Nurs. 2000 Apr;1(4):321-331.