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Review

Analysis of head movements during gait in healthy populations and people with neurological disorders: a systematic review

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ABSTRACT

The Head-Trunk System (HTS) is crucial for maintaining visual acuity and stabilizing the head during activities such as walking. However, no consensus exists on methods for measuring HTS movements during walking. Alterations in HTS function, particularly in head movement, are detectable even in the early stages of neurological disorders (PwND). Therefore, this study aimed to summarize the methods and tools used to evaluate head movements in healthy subjects (HS) and PwND during unperturbed linear gait. This systematic review followed the PRISMA Guidelines and the Cochrane Handbook; the protocol was registered on Open Science Framework. In November 2025, the search was conducted across Scopus, Embase, and PubMed. 27 studies were included after screening. Seventeen studies involved 522 HSs aged 17–80 years. Seven studies included PwND. Due to the heterogeneity of the included studies, only a qualitative analysis was conducted. Among HS, the most frequently reported outcome was sagittal plane head angular displacement, averaging 5–10°. In contrast, none of the studies involving PwND reported head angular displacement as an outcome. Other parameters included shock absorption, harmonic ratio, head acceleration, and speed. Significant differences were observed between HS and PwND. Our study reviewed all outcomes and methodologies used to assess head movements. Despite the heterogeneity of the outcomes, this review emphasizes the importance of evaluating head stability during gait by comparing HS and PwND. This could be significant for researchers in designing future studies and for clinicians planning exercises to enhance head stabilization during walking.

1. Introduction

Human locomotion requires intricate coordination of the trunk, neck, and head to maintain gaze stability, which is essential for exploring the environment and focusing on specific targets and goals. These body segments form the head-trunk system (HTS) (Barnes and Smith, 1981).

The central nervous system exerts top-down control over the HTS through three control mechanisms (Di Fabio and Emasithi, 1997; McCarthy et al., 2023). The first is the Vestibulo-Ocular Reflex (VOR), producing head and eye adaptations based on information from the vestibular area. The VOR can be categorized into three subtypes based on the plane of movement in which adaptation occurs (i.e., rotational VOR, translational VOR, and ocular counterrotation) (Dieterich and Brandt, 1995). The second mechanism relies on the visual system, which operates through reflexes; for instance, the optokinetic system triggers ocular nystagmus during repeated head rotations without vestibular input (Robinson, 2022). The third mechanism involves the somatosensory system, which adjusts the responses of the vestibular and ocular systems through proprioceptive information from its receptors in the

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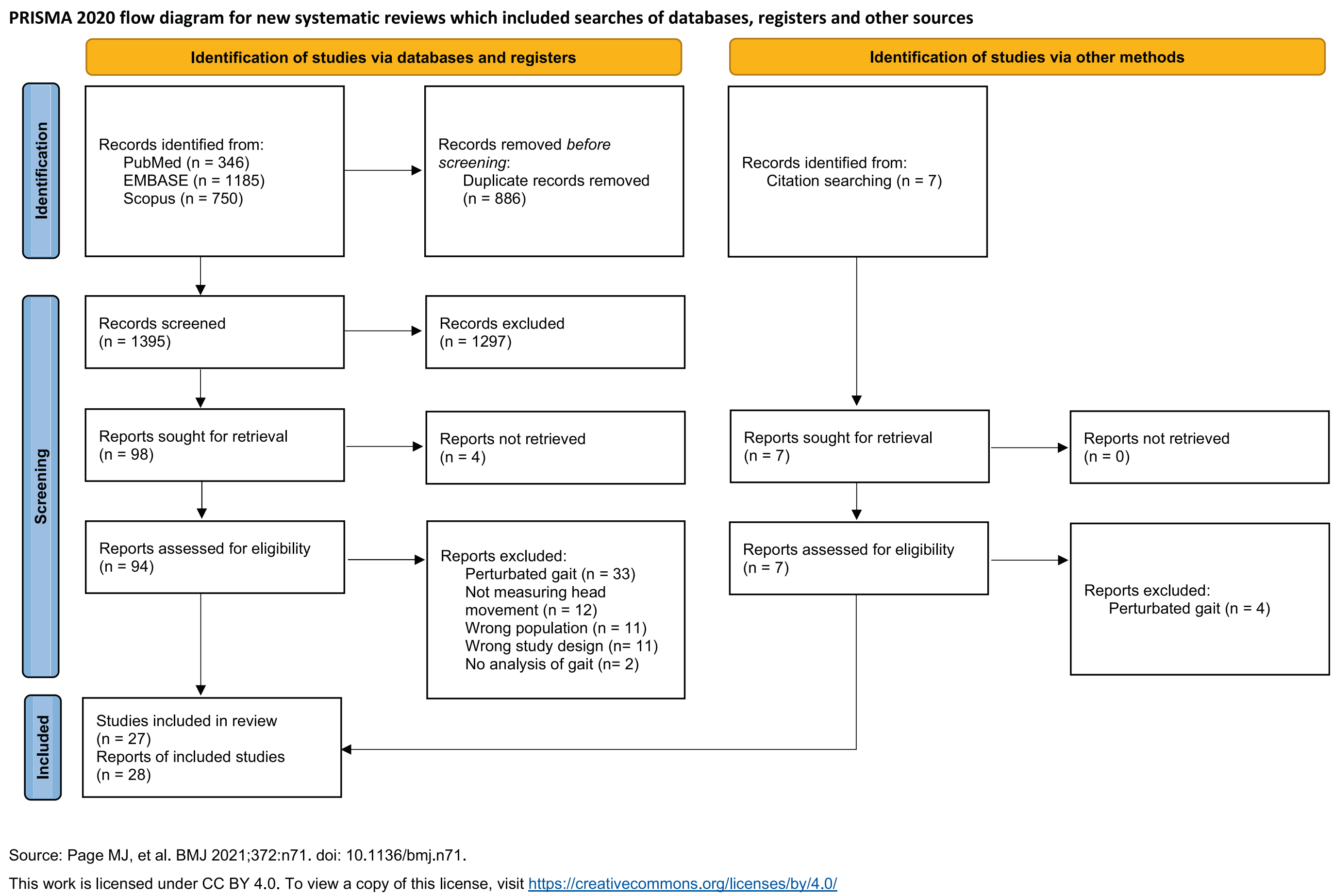

Fig. 1. PRISMA flow diagram of the screening process.

HTS (Smulligan et al., 2024). All these mechanisms work conjunctively to effectively stabilize the head, as this stability is crucial for the proper functioning of the ocular and vestibular systems. Moreover, integrating the three control mechanisms is essential for maintaining balance and coordination and preventing falls (Cinelli and Warren, 2012; Kavanagh et al., 2005; Mulavara et al., 2002).

Extensive literature has examined the HTS across various activities (Andreoni et al., 2003; Pozzo et al., 1989; Weston et al., 2022), showing that among studies primarily focusing on head stability within the HTS, walking is the most frequently investigated task in healthy subjects (HS). However, head control relies on the integrity of the central and peripheral nervous systems, particularly in the brain and spinal regions. Conditions that compromise these areas, such as neurodegenerative diseases, movement disorders, or traumatic injuries, can significantly affect the ability to control head stabilization. Consequently, neurological disorders such as Stroke, Parkinson's disease, and Multiple Sclerosis may disrupt head stability during walking, leading to balance issues and incoordination and increasing the risk of falling (Borel et al., 2002; Carpinella et al., 2021; Loyd et al., 2023). Moreover, people with neurological disorders may display symptoms like muscle weakness, spasticity, coordination and balance difficulties, fatigue, and visual and vestibular disorders (Loyd et al., 2022; Wetzel et al., 2011) that could affect the head-trunk function and subsequently alter head control (Pau et al., 2017), even in the early stages of the disease (Carpinella et al., 2021; Kammermeier et al., 2025). These conditions force people with neurological disorders to reduce their walking speed (Wetzel et al., 2011) and significantly increase the risk of falling (Close et al., 2005; Morrison et al., 2016). As a result, several studies have examined the acceleration patterns of specific body segments, offering insights into gait changes. (Craig et al., 2020, 2017).

Numerous studies have explored various methodologies, tools, and instruments for measuring head movements (Cromwell et al., 2004; Pozzo et al., 1991). However, there is no consensus or comprehensive synthesis to summarize the employed methodologies. The findings garnered from these studies could offer valuable insights, especially in the biomechanical field, where methodological discrepancies appear to affect the certainty of primary studies (Knudson, 2017). Therefore, this systematic review aims to synthesize the procedures, instruments, and outcome measures used to assess head movements during linear gait in both HS and people with neurological disorders.

2. Methods

This systematic review was conducted following the Cochrane Handbook's methodology version 6.4. The information was reported based on PRISMA guidelines, and the protocol was registered on Open Science Framework: Doi: 10.17605/OSF.IO/87THP.

2.1. Search strategy and PICO

The search strategy's inclusion and exclusion criteria were based on the PICO framework, as follows: Population: HS and/or People with Multiple Sclerosis (PwMS), People with Parkinson's Disease (PwPD), People with Stroke (PwStroke), with age ≥18 years; Intervention: no intervention applied; Comparison: not integrated; Outcome: measures of head movement in all directions during linear gait.

The search strategy (see Supplementary Material 1) was designed and conducted in three electronic databases (Scopus, Embase, and PubMed). Records were identified and imported into Zotero version 6.0.30 on the 24th of November 2025 to delete multiple references. Two

Table 1
Characteristics of the included studies.

Study ID	Country	Study Design	METHODS			HEALTHY				Neurological disorders				
			Activity	Pace	Gait Speed	Healthy subjects	Age [years]	Sex [Female; Male]	Other parameters	Number of PwND	Age [years]	Sex	Disease parameter	Other disease parameters
Brodie 2013	Australia	Cross-Sectional	O	Slow speed Preferred speed Fast speed	0.61 ± 0.17 1.4 ± 0.4 2.0 ± 0.3	13	32 ± 6	4;9	NR	NA	NA	NA	NA	NA
Cromwell 2001a	USA	Observational Study with Case-Series	O	Preferred speed	NR	8	25.6 ± 3.3	2;6	NR	NA	NA	NA	NA	NA
Cromwell 2002	USA	Case-control	O	Preferred speed	YG 1.4 ± 0.2 m/s OG 1.2 ± 0.2 m/s	YG: 20 OG: 17	YG: 26.0 ± 3.4 OG: 76.2 ± 6.9	YG: 11;9 OG: 11;6	YG: Neck flexion range of motion: 47.4° ± 6.4° Visual acuity: 20/20 BBT: 56.0 ± 0.0 Activities-Specific Balance Confidence Scale: 28.4 ± 2.6 Neck flexion range of motion: 41.2° ± 10.3° Visual acuity: 20/30 BBT: 53.1 ± 3.3 Activities-Specific Balance Confidence Scale: 24.4 ± 4.9	NA	NA	NA	NA	NA
Cromwell 2001b & Cromwell 2004	USA	Cross-sectional	O	Preferred speed	NR	8	27.1 ± 5.1	3;5	NR	NA	NA	NA	NA	NA
Deshpande 2014	Canada	Case-control	O	Preferred speed	YG: 1.12 ± 0.04 OG: 1.08 ± 0.03	YG: 15 OG: 15	YG: 25 ± 3.56 OG: 73 ± 5.34	YG: 7;8 OG: 8;7	NR	NA	NA	NA	NA	NA
Hausamann 2019	Germany	Cross-Sectional	O	NR	NR	10	21 to 28	5;5	NR	NA	NA	NA	NA	NA
Hausamann 2021	USA	Cross-Sectional	O	Preferred speed	NR	9	27.8 [20–46]	5;4	NR	NA	NA	NA	NA	NA

(continued on next page)

Table 1 (*continued*)

Study ID	Country	Study Design	METHODS			HEALTHY				Neurological disorders				
			Activity	Pace	Gait Speed	Healthy subjects	Age [years]	Sex [Female; Male]	Other parameters	Number of PwND	Age [years]	Sex	Disease parameter	Other disease parameters
Hirasaki 1992	Japan	Case-control	O	Slow Walk Preferred speed	NR NR	YG: 10 OG: 8	<40 >60	NR	NR	NA	NA	NA	NA	NA
Kavanagh 2006	Australia	Cross-Sectional Study	O	Slow speed Preferred Speed Fast speed	1.01 ± 0.14 1.35 ± 0.12 1.86 ± 0.28	8	23 ± 4	8	NR					
Latt 2007	Australia	Cross-Sectional Study	O	Very slow Slow Preferred Speed Fast Very fast	0.5 ± 0.05 0.88 ± 0.18 1.2 ± 0.04 1.70 ± 0.26 2.1 ± 0.1	10	26 ± 5.3	6;4	NR	NA	NA	NA	NA	NA
Maslivec 2017	UK	Case-Control	O	Slow speed Preferred Speed Fast Speed	YG 1.05 ± 0.15 OG 0.94 ± 0.21 YG 1.58 ± 0.20 OG 1.32 ± 0.28 YG 2.37 ± 0.30 OG 1.81 ± 0.20	YG 15 OG 16	YG 23 ± 3.5 OG 75.5 ± 6.2	YG 15;0 OG 16;0	NR	NA	NA	NA	NA	NA
Mazzà 2008	Italy	Case-control	O	Preferred speed Fast gait	YG: 1.30 ± (0.07) OG: 0.97 ± (0.04) YG: 2.32 ± (0.05) OG: 1.59 ± (0.04)	YG: 16 OG: 20	YG: 24 ± 4 OG: 72 ± 4	36;0	NR	NA	NA	NA	NA	NA
Mazzà 2009	Italy	Case-control	O	Preferred speed Fast gait	Female 1.34 ± (0.02) Male 1.33 ± (0.03) Female 1.87 ± (0.03) Male 1.95 ± (0.03)	40	Female: 23 ± 3 Male: 23 ± 2	20;20	NR	NA	NA	NA	NA	NA
Nadeau 2003	Canada	Cross-sectional study	O	Preferred speed	1.10 ± 0.21 m/s	11	27.6 ± 4.2	6;5	NR	NA	NA	NA	NA	NA
Pozzo 1989	France	Cross-sectional study	O	Preferred speed	NR	10	20 to 45	1;9	NR	NA	NA	NA	NA	NA

(*continued on next page*)

Table 1 (*continued*)

Study ID	Country	Study Design	METHODS			HEALTHY				Neurological disorders				
			Activity	Pace	Gait Speed	Healthy subjects	Age [years]	Sex [Female; Male]	Other parameters	Number of PwND	Age [years]	Sex	Disease parameter	Other disease parameters
Pozzo 1990	France	Cross-sectional study	O	Preferred speed	[1.3–1.8] m/s	10	20 to 45	1;9	NR	NA	NA	NA	NA	NA
Thomas 2020	UK	Cross-sectional study	O	Preferred speed	1.35 ± 0.04 m/s	11	24.6 ± 3.5	4;7	NR	NA	NA	NA	NA	NA
Thumser 2009	USA	Cross-sectional study	O	NR	NR	19	23 to 61	8;11	NR	NA	NA	NA	NA	NA
Usumez 2006	Turkey	Cross-sectional study	O	Preferred speed	NR	50	20 to 25	25;25	NR	NA	NA	NA	NA	NA
Studies including People with Multiple Sclerosis														
Cattaneo 2005	Italy	Case control, with a single case study	T	Imposed	1 km/h	20	40.5 ± 16.8	11;9	TUG time [s]: 8.5 ± 2.4	23	47.8 ± 10.7	15;8	NA	TUG time: 16.7 ± 10.3
Morrison 2022	USA	Cross-sectional study	O	Self-selected	NR	NA	NA	NA	NR	23	56.1 ± 9.1	17;6	EDSS → NR	MS duration: 17.8 ± 12.9 MFES-I score: 7.3 ± 2.1 Average ABC score (%): 56.8 ± 21.2 Average PDDS score: 3.39 ± 1.6
Psarakis 2018	Australia	Case-control	O	Preferred speed	NR	12	55.8 ± 12.23	8;4	6MWT: 506 ± 82.64 m Passive ankle ROM: 96.6° ± 5.92° Active ankle ROM: 102.4° ± 5.95°	12	52.0 ± 9.1	9;3	EDSS ≤ 6	6MWT: 330 ± 112 m Passive ankle ROM: 87.9° ± 7.8° Active ankle ROM: 65.5° ± 15.8°
Studies including People with Parkinson's Disease														
Buckley 2015	UK	Case-Control	O	Self-selected	HC: 1.32 ± 0.15 PD 1.22 ± 0.22	19	70.2 ± 6.7	NR	NR	13	69.7 ± 11.1	NR	UPDRS III 35.6 ± 12.6	HY II: 11; HY III: 2
Cole 2010	Australia	Case-Control	O	Self-selected	Healthy non-faller 1.28 ± (0.05) Healthy faller 1.22 ± (0.04) PD non-faller 1.15 ± (0.04) PD faller 1.03 ± (0.04)	Healthy non-faller 17 Healthy faller 17	Healthy non-faller 65.1 ± 2.1 Healthy faller 70.2 ± 2.3	Healthy non-faller 7;10 Healthy faller 7;10	NR	PD non-faller 17 PD faller 32	PD non-faller 66.9 ± (2.1) PD faller 66.2 ± (1.4)	PD non-faller 4;13 PD faller 12;20	PD non-faller 26.6 ± (3.7) PD faller 34.5 ± (2.7)	HY PD non-faller 1.6 ± (0.2) PD faller 1.8 ± (0.1)
Latt 2009	Australia	Case-Control	O	Self-selected	HC 1.24 ± 0.06 PD non-faller:	33	67 ± 4	18;15	NR	PD non-faller 33	PD non-faller 63 ± 4	PD non-faller	PD non-faller 25 ± 4	UPDRS III PD non-faller 12 ± 3

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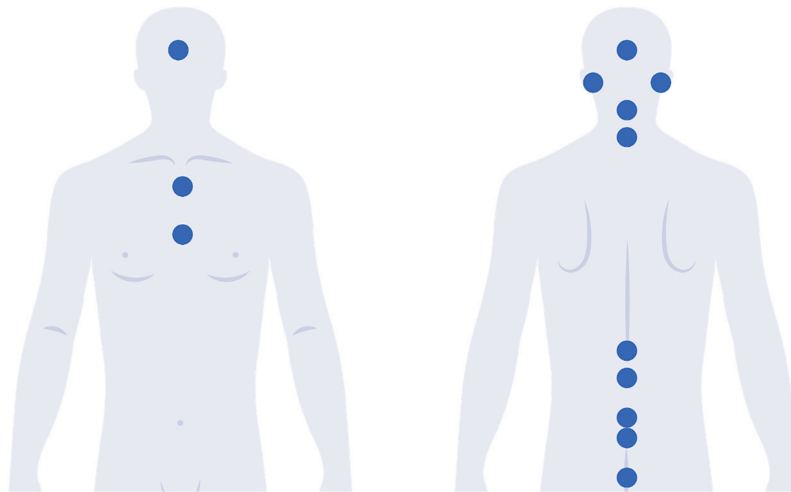
Table 1 (*continued*)

Study ID	Country	Study Design	METHODS			HEALTHY				Neurological disorders				
			Activity	Pace	Gait Speed	Healthy subjects	Age [years]	Sex [Female; Male]	Other parameters	Number of PwND	Age [years]	Sex	Disease parameter	Other disease parameters
					1.09 ± 0.07 PD faller: 0.78 ± 0.06					PD faller 33	PD faller 67 ± 2	18;5 PD faller 18;15	PD faller 42 ± 5	PD faller 21 ± 3 HY PD non-faller [1–1] PD faller [3–1]
Pelicioni 2018	Australia	Case-Control	O	Self-selected	Non-PIGD: off 1.10 ± 0.25 on 1.16 ± 0.28 PIGD: off 0.97 ± 0.32 on 0.98 ± 0.33	NA	NA	NA	NA	non-PIGD 15 PIGD 23	non-PIGD 63.0 ± 7.6 PIGD 62.6 ± 10.0	non-PIGD 7;8 PIGD 8;15	UPDRS total non-PIGD 33.5 ± 20.7 PIGD45.8 ± 15.5	UPDRS III non-PIGD 16.3 ± 11.4 PIGD 22.4 ± 10.9 HY non-PIGD 2.2 ± 0.9 PIGD 1.5 ± 0.7
Studies including People with Stroke														
Bergamini 2017	Italy	Case-Control	O	Self-selected	HC [1.19–0.21] SG1 [0.41–0.25] SG2 [0.66–0.29] SG3 [0.83–0.28]	25	54 ± 8	6;19	NR	45	63 ± 13	27;18	Subacute stroke	TBG SG1 [17.5–3.5] SG2 [21–4.5] SG3 [25–2] BBS SG1 [37.5–10.2] SG2 [45–7] SG3 [50–4] BI SG1 [84.5–18.7] SG2 [91.5–12.5] SG3 [100–3]

Data expressed in Mean ± Standard Deviation, Mean ± (SEM), Mean [range]; [median – IQR]; Sex expressed in Female;Male. Abbreviations EDSS: Expanded Disability Status Scale; NR: Not reported; NA: Not Applicable; T: Treadmill; O: Overground; PwND: People with Neurological Disorders; YG: Young adults group; OG: Older adults group; HC: Healthy Control; SG1: Stroke Group 1; SG2: Stroke Group 2; SG3: Stroke Group 3; TUG: Time Up & Go; BBT: Berg Balance Test; MFES-I: Modified Falls Efficacy Scale-International; ABC: Activities-specific Balance Confidence; PDDS: Patient Determined Disease Steps; 6MWT: 6-minute walking test; ROM: Range of Motion; PD: Parkinson's Disease; PIGD: Postural Instability and Gait difficulty; TBG: Tinetti Balance and Gait Scale; BBS: Berg Balance Scale; BI: Barthel Index; HY: Hoehn and Yahr.



Positioning	Number of studies	ID
Head	13	Brodie 2013; Cattaneo 2005; Hausamann 2019; Hausamann 2021; Hirasaki 1992; Latt 2007; Latt 2009; Mazzà 2008; Mazzà 2009; Pelicioni 2018; Psarakis 2018; Thumser 2009; Usumez 2006;
Head (ear level)	2	Cromwell 2004 & 2001
Forehead	2	Kavanagh 2006; Thomas 2020;
Occipital pole	3	Bergamini 2017; Buckley 2015; Morrison 2022
C7 spinous process	5	Buckley 2015; Kavanagh 2006; Mazzà 2008; Mazzà 2009; Morrison 2022;
Sternum	1	Thumser 2009

Positioning	Number of studies	ID
Xiphoid process	2	Cromwell 2004 & 2001b;
L2 spinous process	1	Latt 2007
L3 spinous process	2	Kanavagn 2006; Morrison 2022
L4-L5 level	1	Bergamini 2017
L5 spinous process	1	Buckley 2015;
Sacrum	6	Hausamann 2019; Latt 2009; Mazzà 2008; Mazzà 2009; Pelicioni 2018; Psarakis 2018;

Fig. 2. Graphical representation of the IMUs positioning across the included studies.

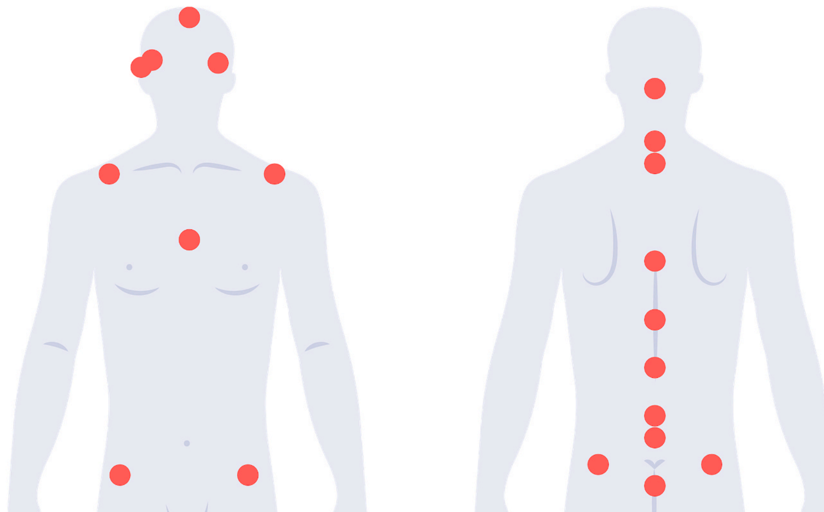
independent reviewers (P.J. and D.M.A.) screened titles and abstracts using Rayyan (Ouzzani et al., 2016) and subsequently proceeded to full-text screening. The reviewers were blinded to each other until the end of the screening process, and a third reviewer (G.E.) was consulted to resolve any disagreements. Furthermore, references of the included studies were screened to identify further relevant articles for this review.

2.2. Eligibility criteria

During the whole screening process, only records in English were considered. Studies including HS and PwMS, PwStroke, and PwPD aged $\geq$ 18 years were included. HS had to be free from any musculoskeletal disorder or neurological impairment. We considered all available instruments measuring head movements in all directions. Records were excluded if they provided measurements during sports activities or activities other than linear walking overground or on a treadmill. We excluded any intervention that could modify walking, such as asking the participant to maintain gaze or rotate their head. We also excluded Case Reports, Case Series, Study Protocols, theses, and conference abstracts.

2.3. Data extraction

Two researchers (P.J. and D.M.A.) extracted all relevant data from the included studies into an Excel sheet prepared by P.J., in which qualitative and quantitative data were synthesized. We extracted descriptive information, including the year of publication, study design, and the number of assessments. We also extracted information on the population, the number of participants, age, sex, specific information related to the pathology (e.g., EDSS level, UPDRS score, or Fugl-Meyer score), any subgroups, and methods for measuring head movements during walking. We considered all head movements in the planes of space to compare and summarize the outcomes of the studies. If these



Positioning	Number of studies	ID
Top of the head	5	Cole 2010; Cromwell 2001a; Cromwell 2002; Deshpende 2014; Hausamann 2021;
Ears	3	Cole 2010; Deshpende 2014; Hirasaki 1992;
The line between the eye lateral canthus and the meatus of the ear	2	Pozzo 1989; Pozzo 1990;
Eye lateral canthus	1	Hirasaki 1992;
C0-C1 joint	1	Cromwell 2001a;
C6-C7 joint	3	Cole 2010; Cromwell 2001a; Cromwell 2002;
C7 spinous process	2	Deshpende 2014; Nadeau 2003;
Sternum	1	Cole 2010;
Acromion	5	Cole 2010; Deshpende 2014; Hirasaki 1992; Pozzo 1989; Pozzo 1990;
Humerus olecranon	1	Cole 2010;

Positioning	Number of studies	ID
Elbow lateral condyle	2	Pozzo 1989; Pozzo 1990;
Radial styloids	3	Cole 2010; Pozzo 1989; Pozzo 1990;
Ulnar styloids	1	Cole 2010
T6 spinous process	1	Nadeau 2003;
T12 spinous process	2	Deshpende 2014; Nadeau 2003;
L3 spinous process	1	Nadeau 2003;
L5 spinous process	1	Nadeau 2003;
L5-S1 joint	2	Cromwell 2001a; Cromwell 2002;
Tubercle of the iliac crest	2	Pozzo 1989; Pozzo 1990;
Sacrum or S2 level	2	Cole 2010; Deshpende 2014;
Posterior iliac spine of the pelvis	1	Nadeau 2003;

Fig. 3. Graphical representation of markers' positioning in the included studies.

parameters were unavailable from the text, we extracted them from the graphs through WebPlotDigitizer version 4.7 (https://automeris.io/). Regarding missing data, we contacted the authors to provide further details. However, none of the contacted authors replied.

2.4. *Analysis of results*

The data obtained were qualitatively compared to verify the consistency and homogeneity of reporting measures used to assess head movements.

2.5. *Risk of bias assessment*

The quality assessment and risk of bias were done simultaneously with the data extraction process by the same two reviewers (P.J. and D. M.A.). Given the study design, we assessed the methodological quality of the studies using the Joanna Briggs Institute (JBI) checklists (26), selecting the appropriate checklist for each study design.

3. Results

The database search identified 2281 results, and seven other records were identified through reference screening of reports retrieved in the full-text screening phase. After the screening process, 28 reports (Bergamini et al., 2017; Brodie et al., 2014; Buckley et al., 2015; Cattaneo et al., 2005; Cole et al., 2010; Cromwell et al., 2004, 2002; Cromwell et al., 2001a; Cromwell et al., 2001b; Deshpande and Zhang, 2014; Hausamann et al., 2021, 2019; Hirasaki et al., 1992; Kavanagh et al., 2006; Latt et al., 2009, 2008; Maslivec et al., 2017; Mazzà et al., 2009, 2008; Morrison et al., 2022; Nadeau et al., 2003; Pelicioni et al., 2018; Pozzo et al., 1990, 1989; Psarakis et al., 2018; Thomas et al., 2020; Thumser and Stahl, 2009; Usumez et al., 2006) were included, containing the information of 27 studies. All the included studies were observational trials, 14 cross-sectional studies, and 13 case-control

Table 2
Angular measurements of the included studies.

Study ID	Range of Motion [°]			Angular velocity [°/s]			Angular displacement frequency [Hz]			Other angular parameters
	Pitch	Yaw	Roll	Pitch	Yaw	Roll	Pitch	Yaw	Roll	
Healthy Subjects										
Cattaneo 2005	2.18 ± (0.21)	2.09 ± (0.16)		31.81 ± (3.42)	41,10 ± (5.03)		2.58 ± (0.12)	4.04 ± (0.24)		
Cromwell 2001a	12.11 ± NR									Angular position [°]: Head 79.44 ± 2.89 Neck 89.97 ± 4.38 Trunk 82.13 ± 1.67 Maximum excursion [°]: Neck 17.98 Trunk 6.68
Cromwell 2002				YG: 51.6 ± 14.7 OG: 31.7 ± 11.0						
Deshpande 2014	YG: 6.47 ± 3.75 OG: 6.89 ± 1.01		YG: 2.82 ± 0.53 OG: 4.38 ± 2.01							
Hirasaki 1992	YG: 8.88 ± 3.73 OG: 15.58 ± 6.29									
Maslivec 2017	YG: Slow − self-selected 1.33 ± 0.58 self-selcted −fast 0.34 ± 0.08 OG: slow – self- selected 4.12 ± 0.79 self-selected −fast 2.09 ± 1.09									
Nadeau 2003	2.16 ± 0.95		1.43 ± 0.66							
Pozzo 1989	8 ± 2	11 ± 5		28 ± 7	25 ± 12					
Pozzo 1990	8.5 ± 2.5			30.25 ± 7.60						
Thomas 2020	−2.15 ± (0.52)									
Usumez 2006	4.60 ± 4.66									

YG: Young Group; OG: Old Group; Data presentation: Mean ± Standard Deviation, Mean ± (Standard Error).

studies. The whole screening process is reported in Fig. 1. Reasons for exclusion and the entire selection process are highlighted in the PRISMA flowchart.

3.1. Participants characteristics

The included studies involved 522 HS aged 17–80 years, among whom 259 were females, and 216 were males; one study did not report the subjects' sex (Hirasaki et al., 1992). Two studies (Morrison et al., 2022; Psarakis et al., 2018) included PwMS and recruited 35 participants with a mean ± standard deviation age of 54.7 ± 9.2 years. Four studies considered PwPD, with a total sample of 166 participants, with a mean ± standard deviation age of 65.68 ± 6.44 years (Buckley et al., 2015; Cole et al., 2010; Latt et al., 2009; Pelicioni et al., 2018). Only one study collected data on PwStroke, with a sample of 25 participants, a mean ± standard deviation age of 54 ± 8 years (Bergamini et al., 2017). Participants' demographic data are reported in Table 1.

3.2. Analysis of the studies' methodology

The included studies examined head movements during gait in different conditions. Most studies collected data during overground walking: 25 involved HS, 2 involved only PwMS and PwPD, respectively, and 1 recruited PwStroke, mostly at spontaneous speed. In contrast, only one study, involving PwMS, collected data on a treadmill at a constant speed (i.e., 1 km/h) (Cattaneo et al., 2005).

Regarding instrumental tools, inertial sensors were used in 15 studies (Bergamini et al., 2017; Brodie et al., 2014; Cattaneo et al., 2005; Cromwell et al., 2004; Hausamann et al., 2019; Kavanagh et al., 2006; Latt et al., 2009, 2008; Mazzà et al., 2009; Morrison et al., 2022; Pelicioni et al., 2018; Psarakis et al., 2018; Thomas et al., 2020; Thumser and Stahl, 2009; Usumez et al., 2006) with a variable number of Inertial Measurement Units (IMUs) (one study used 1 IMU, 10 studies used two IMUs, two studies used three IMUs, one study used four IMUs, and one study used 5 IMUs). These studies used different anatomical reference points in their assessment setting. The graphical representation of the anatomical landmarks used in the studies is shown in Fig. 2, and their descriptions are provided in Supplementary Material 2. Nine studies utilized optoelectronic systems (Cole et al., 2010; Cromwell et al., 2002; Cromwell et al., 2001a; Cromwell et al., 2001b; Deshpande and Zhang, 2014; Maslivec et al., 2017; Mazzà et al., 2008; Nadeau et al., 2003; Pozzo et al., 1990, 1989) with a different number of cameras and using passive and active markers; one of these studies combined an optoelectronic system with surface electromyography. Data acquisition frequencies ranged from 0.5 Hz to 500 Hz across studies. The marker-set position varied across the studies (see Fig. 3 and Supplementary Material 2. Finally, three studies used both IMUs and optoelectronic systems, the first validating the reliability of single IMU measurements (Hirasaki et al., 1992), the second using optoelectronics for gait assessment and IMUs for head movement analysis (Hausamann et al., 2021), and the third using optoelectronics for gait assessment and IMUs for the upper body (Buckley et al., 2015).

3.3. Measurements of head movements

The head movement data from all included studies were extracted,

Table 3
Head accelerations in the included studies across different speed conditions.

Study ID	RMS Head Acceleration [m/s^2]					
	Healthy subjects			Neurological disorders		
	Pitch	Yaw	Roll	Pitch	Yaw	Roll
Kavanagh 2006	SS: 0.06 ± (0.00) PS: 0.08 ± (0.02) FS: 0.12 ± (0.01)	SS: 0.07 ± (0.01) PS: 0.08 ± (0.02) FS: 0.09 ± (0.01)	SS: 0.10 ± (0.01) PS: 0.16 ± (0.03) FS: 0.30 ± (0.02)			
Latt 2007	VSS: 0.03 ± 0.01 SS: 0.06 ± 0.02 PS: 0.1 ± 0.02 FS: 0.16 ± 0.1 VFS: 0.19 ± 0.11	VSS: 0.02 ± 0.01 SS: 0.04 ± 0.02 PS: 0.05 ± 0.03 FS: 0.08 ± 0.03 VFS: 0.08 ± 0.03	VSS: 0.04 ± 0.02 SS: 0.9 ± 0.04 PS: 0.19 ± 0.05 FS: 0.34 ± 0.16 VFS: 0.37 ± 0.23			
Mazzà 2008	PS: YG 0.41 ± (0.02) OG 0.41 ± (0.02) FS: YG 0.65 ± (0.07) OG 0.70 ± (0.07)	PS: YG 0.39 ± (0.03) OG 0.49 ± (0.03) FS: YG 0.67 ± (0.06) OG 0.65 ± (0.05)	PS: YG 1.68 ± (0.21) OG 1.01 ± (0.07) FS: YG 2.90 ± (0.27) OG 1.94 ± (0.15)			
Mazzà 2009	PS: Female 0.61 ± (0.03) Male 0.80 ± (0.06) FS: Female 0.88 ± (0.05) Male 1.06 ± (0.07)	PS: Female 0.76 ± (0.04) Male 1.08 ± (0.07) FS: Female 1.05 ± (0.05) Male 1.35 ± (0.07)	PS: Female 2.90 ± (0.09) Male 8.80 ± (0.15) FS: Female 4.37 ± (0.14) Male 4.43 ± (0.12)			
Healthy subjects				**People with Multiple Sclerosis**		
Morrison 2022				PS: 0.10 ± (0.005)	PS: 0.10 ± (0.005)	PS: 0.14 ± (0.01)
Healthy subjects				**People with Parkinson's Disease**		
Buckley 2015	0.92 ± 0.20	0.86 ± 0.21	2.41 ± 0.47	1.02 ± 0.24	1.08 ± 0.29	2.15 ± 0.74
Latt 2009	0.11 ± 0.02	0.09 ± 0.02	0.17 ± 0.02	PD non-faller: 0.09 ± 0.01 PD faller: 0.07 ± 0.01	PD non-faller: 0.07 ± 0.02 PD faller: 0.05 ± 0.01	PD non-faller: 0.14 ± 0.02 PD faller: 0.08 ± 0.02
Healthy subjects				**People with stroke**		
Bergamini 2017	[0.50–0.08]	[0.62–0.08]	[1.12–0.22]	SG1 [1.68–1.13] SG2 [0.88–0.24] SG3 [0.68–0.24]	SG1 [1.88–0.44] SG2 [0.84–0.29] SG3 [0.73–0.21]	SG1 [0.50–0.08] SG2 [0.50–0.08] SG3 [0.50–0.08]

YG: Young Group; OG: Old Group; PD: Parkinson's Disease; SG1: Stroke Group 1; SG2: Stroke Group 2; Stroke Group 3; VSS: Very Slow Speed; SS: Slow speed; PS: Preferred speed; FS: Fast speed; VFS: Very Fast Speed; Data presentation: Mean ± Standard Deviation, Mean ± (Standard Error), [median – IQR].

except for Hausamann 2021 and Hausamann 2019, whose data were presented in an unusable format (Hausamann et al., 2021,2019).

The most assessed outcome was head angular displacement [degrees, °], of which ten studies measured pitch (on the sagittal plane) (Cattaneo et al., 2005; Cromwell et al., 2001a; Cromwell et al., 2001b; Deshpande and Zhang, 2014; Hirasaki et al., 1992; Maslivec et al., 2017; Nadeau et al., 2003; Pozzo et al., 1990, 1989; Thomas et al., 2020; Usumez et al., 2006), two studies roll (on the frontal plane), and two studies yaw (on the transversal plane) (Table 2). All these studies involved only HS. The measures obtained in these studies reported pitch and angular displacement ranging from 2° to 10°, yaw movement ranging from 2° to 11°, and roll ranging from 2° to 5°. Similarly, head angular speed [degrees/seconds, °/s] in HS differed among studies, ranging between 20 and 50°/s in the pitch and yaw movements (Cattaneo et al., 2005; Cromwell et al., 2004, 2002; Cromwell et al., 2001a; Cromwell et al., 2001b; Pozzo et al., 1990, 1989). In contrast, angular speed was not assessed in all included studies for roll movement (see Table 2).

Four studies examined head acceleration (meters per second squared [m/s2]) during gait in HS (Kavanagh et al., 2006; Latt et al., 2008; Mazzà et al., 2009, 2008). Root Mean Square acceleration was viewed as an index of head acceleration with values ranging between 0.03 and 1.45 m/s^2 for pitch and yaw. In comparison, higher accelerations from 0.1 to 9.0 m/s^2 were reported for roll movements. Morrison 2022 reported an acceleration of around 0.04 m/s^2 in all the planes for PwMS (Morrison et al., 2022). In PwPD, Buckley and Latt showed a similar RMS acceleration ranging between 0.11 and 0.92 m/s^2 for pitch and yaw, while different values were reported for RMS on the roll plane (Buckley et al., 2015; Latt et al., 2009). Finally, Bergamini reported an RMS acceleration on PwStroke ranging from 0.50 to 0.62 m/s^2 for the pitch and yaw plane, while a value of 1.12 for the roll plane (Bergamini et al., 2017) (Table 3).

The harmonic ratio is another outcome computed from the data of the included studies; in particular, six studies calculated this parameter for head movements in the sagittal, transverse, and vertical planes (Buckley et al., 2015; Kavanagh et al., 2006; Latt et al., 2009; Mazzà et al., 2008; Psarakis et al., 2018). The harmonic ratio is calculated from the Fast Fourier Transform of accelerometric data, the ratio of the sum of odd harmonics to the sum of even harmonics. The results of this calculation provide a dimensionless stability index, with higher values representing better stability. The different studies reported similar results on the sagittal (0.97–2.96 Hz) and transversal (1.33–3.84 Hz) planes. Regarding the vertical plane, results were heterogeneous, ranging from 1.16 to 16.34 Hz. The studies by Kavanagh 2006, Latt 2007, and Mazzà 2008 showed a strong influence of gait speed on this specific parameter. Moreover, Mazzà 2008 showed differences between young and older subjects; older subjects showed higher harmonic ratio values (Table 4).

Finally, ten studies (Bergamini et al., 2017; Buckley et al., 2015; Cromwell et al., 2004, 2002; Cromwell et al., 2001a; Cromwell et al., 2001b; Mazzà et al., 2009, 2008; Morrison et al., 2022; Nadeau et al., 2003) examined shock-absorption strategies. Quantifying the ability of

Table 4
Head harmonic ratio measurements.

Study ID	Head harmonic ratio [Hz]					
	Healthy subjects			Neurological Disorders		
	Pitch	Yaw	Roll	Pitch	Yaw	Roll
Kavanagh 2006	SS: 1.09 ± (0.09) PS: 1.4 ± (0.30) FS: 1.82 ± (0.20)	SS: 1.49 ± (0.14) PS: 1.6 ± (0.11) FS: 1.84 ± (0.19)	SS: 1.19 ± (0.12) PS: 1.34 ± (0.25) FS: 2.26 ± (0.22)	NA	NA	NA
Latt 2007	VSS: 0.97 ± 0.18 SS: 1.45 ± 0.39 PS: 1.84 ± 0.40 FS: 1.75 ± 0.58 VFS: 1.47 ± 0.53	VSS: 1.73 ± 0.71 SS: 2.33 ± 1.14 PS: 2.00 ± 0.66 FS: 1.62 ± 0.88 VFS: 1.56 ± 0.70	VSS: 1.16 ± 0.56 SS: 2.30 ± 1.03 PS: 3.50 ± 0.51 FS: 2.82 ± 1.33 VFS: 1.70 ± 0.78	NA	NA	NA
Mazzà 2008	PS: YG 2.96 ± (0.40) OG 2.60 ± (0.21) FS: YG 1.60 ± (0.18) OG 2.26 ± (0.18)	PS: YG 3.00 ± (0.29) OG 3.84 ± (0.40) FS: YG 1.78 ± (0.21) OG 2.06 ± (0.17)	PS: YG 16.34 ± (1.31) OG 11.26 ± (1.07) FS: YG 11.13 ± (1.79) OG 9.01 ± (1.39)	NA	NA	NA
Healthy controls				**People with Multiple Sclerosis**		
Psarakis 2018	1.62 ± 0.15	1.33 ± 0.15	2.36 ± 0.28	1.22 ± 0.15	1.05 ± 0.20	1.53 ± 0.26
Healthy controls				**People with Parkinson's Disease**		
Buckley 2015	0.53 ± 0.23	1.02 ± 0.38	2.18 ± 0.60	0.71 ± 0.36	1.22 ± 0.56	2.03 ± 0.57
Latt 2009	2.27 ± 0.26	1.41 ± 0.33	4.43 ± 0.42	PD non-faller: 1.72 ± 0.25 PD faller: 1.47 ± 0.27	PD non-faller: 2.50 ± 0.31 PD faller: 2.14 ± 0.34	PD non-faller: 3.09 ± 0.40 PD faller: 2.38 ± 0.44
Pelicioni 2018				non-PIGD: off 1.44 ± 0.17 on 1.55 ± 0.16 PIGD: off 1.27 ± 0.15 on 1.36 ± 0.24	non-PIGD: off 2.40 ± 1.36 on 2.89 ± 0.70 PIGD: off 2.71 ± 1.03 on 2.29 ± 1.10	non-PIGD: off 1.63 ± 0.36 on 1.52 ± 0.28 PIGD: off 1.82 ± 0.28 on 1.60 ± 0.31

YG: Young Group; OG: Old Group; PD: Parkinson's Disease; PIGD: Postural Instability and Gait difficulty; VSS: Very Slow Speed; SS: Slow speed; PS: Preferred speed; FS: Fast speed; VFS: Very Fast Speed; Data presentation: Mean ± Standard Deviation, Mean ± (Standard Error).

the different segments of the HTS (i.e., pelvis, upper trunk, neck, and head) to absorb the accelerations generated by the locomotion activity, aiming to stabilize the head. The studies' findings showed different calculation methods for this outcome, preventing the comparison of data between the included studies; these results are presented in Table 5 and Supplemental Material 2.

Single studies considered other parameters; the complete report on these parameters is available in Supplementary Material 3.

3.4. Differences between HS and PwMS

Psakaris 2018 compared the harmonic ratio of HS and PwMS, showing a significant reduction in PwMS, implying a lower stability level (Psarakis et al., 2018) (Table 4). Studies examining shock absorption have shown that in HS, compensation appears to be primarily performed by the pelvis and secondarily by the upper trunk, whereas in PwMS, the trunk plays a central role in the attenuation strategy. However, heterogeneity in the methodology used to calculate the outcome needs to be considered alongside the limited number of studies investigating shock absorption in PwMS.

3.5. Differences between HS and PwPD

Both Buckley et al and Latt et al reported Harmonic ratio and RMS data comparing HS and PwPD. Latt reported statistically significant differences between HS and PwPD in both outcomes (Latt et al., 2009), whereas Buckley found a difference in RMS only in the medio-lateral plane and no difference in HR (Buckley et al., 2015). Buckley also reported that PwPD were unable to attenuate trunk accelerations in both the AP and ML directions compared to HS.

3.6. Differences between HS and PwStroke

Bergamini et al. showed a statistically significant difference between HS and PwStroke in RMS values, attenuation coefficients, and symmetry indices (Bergamini et al., 2017).

3.7. Risk of bias in the included studies

The appropriate JBI checklists were used for the included cross-sectional (n = 14) and case-control (n = 13) studies. The reports and items are presented in Tables 6 and 7.

Considering cross-sectional studies (Table 6), Items 1, 2, 3, and 4 of the JBI checklist were correctly addressed, with completeness of 93%, 86%, 93%, and 100%, respectively. Key issue, including recognizing and managing confounding factors. Specifically, 36% and 50% lacked clear identification, while 21% and 36% had ambiguous identification. Item 7 was correctly addressed in 86% of studies, and item 8 was correctly reported in 79%, while 21% showed unclear results regarding the correctness of the proposed statistical analysis.

Considering Case-control studies (Table 7), items 1, 2, 3, 4, and 5 exhibited little to no issues, with a positive score in all included studies for items 1 and 4 and an upbeat score in 12 over thirteen included studies in item 2, 3, and 5 (1 study with unclear result in item 2, and respectively one study with not correct reporting for item 3 and 5). Items 6 and 7 showed flaws in identifying and managing confounding factors, with reporting issues in 4 studies (3 incorrect and 1 unclear) and 7 studies (3 incorrect and 4 unclear). Items 8 and 10 were correctly presented and managed in all studies; item 9 was correctly administered in 5 studies, and in 8 studies, it was not applicable.

4. Discussion

This systematic review highlighted evidence on head movement during unperturbed linear gait in HS and the impact of neurological disorders on head stability. After the screening process, 27 studies were

Table 5
Shock absorption values in the different districts.

Study ID	Parameter computation	Shock absorption: Healthy subjects: Antero-Posterior	Healthy subjects: Medio-Lateral	Healthy subjects: Vertical	Neurological Disorders: Antero-Posterior	Neurological Disorders: Medio-Lateral	Neurological Disorders: Vertical
Cromwell 2001a	The coefficient of variation is an index of stability.	Coefficient of variation (%): Head 2.03 Neck 4.87 Trunk 2.03					
Cromwell 2002	To examine control strategies used to maintain head stability, we examined head-on-trunk movement concerning trunk-in-space motion. That analysis provided information about the coordination of the head and trunk. Participants achieved complete compensatory movement by making equal and opposite movements between head-on-trunk and trunk movements. Complete compensations would result in a gain of 1.0 accompanied by a phase 180°.	Gain: YG 1.5 ± 0.8 OG 1.2 ± 0.6 Phase degree: YG 185.6 ± 36.1 OG 187.3 ± 35.9					
Cromwell 2001b & Cromwell 2004		Gain 1.2 ± 0.3 Phase 190.9 ± 10.5					
Mazzà 2008	The ability to attenuate the accelerations from pelvis to head level (Cph) and shoulder to head level (Csh). It is essential to highlight that these coefficients, evaluated as a ratio between accelerations, are expected to be independent of the stride frequency of each trial under analysis. Higher values of the coefficients indicate a more effective head stabilization strategy and a higher reduction of the inertial loads.	Cph: PS YG 69.76 ± (2.53) OG 60.06 ± (2.53) FS YG 71.23 ± (1.05) OG 57.21 ± (3.27) Csh: PS YG 45.94 ± (3.38) OG 33.09 ± (5.90) FS YG 38.46 ± (2.53) OG 9.17 ± (4.63)	Cph: PS YG 13.98 ± (5.81) OG −5.81 ± (6.75) FS YG 22.04 ± (6.04) OG −6.52 ± (6.16) Csh: PS YG 1.78 ± (5.80) OG 2.96 ± (5.69) FS YG 1.06 ± (2.72) OG −3.08 ± (3.56)	Cph: PS YG −2.20 ± (2.26) OG −2.09 ± (3.20) FS YG 9.14 ± (2.29) OG 8.23 ± (3.2) Csh: PS YG −0.37 ± (1.33) OG −0.25 ± (2.71) FS YG −0.25 ± (0.87) OG 9.72 ± (1.71)			
Mazzà 2009		Cph: PS Female 69.89 ± (2.24) Male 56.40 ± (3.6) FS Female 72.13 ± (2.25) Male 62.70 ± (4.04) Csh: PS Female 43.80 ± (2.96) Male 25.21 ± (3.38) FS Female 38.73 ± (2.96) Male 26.48 ± (2.96)	Cph: PS Female 58.65 ± (2.70) Male 28.99 ± (4.39) FS Female 66.74 ± (2.25) Male 43.37 ± (3.60) Csh: PS Female 20.56 ± (3.38) Male −6.90 ± (2.96) FS Female 23.52 ± (3.80) Male −0.14 ± (3.80)	Cph: PS Female −0.67 ± (2.25) Male −5.17 ± (2.25) FS Female 2.47 ± (2.25) Male −2.47 ± (2.70) Csh: PS Female −11.97 ± (1.69) Male −14.08 ± (1.69) FS Female −12.82 ± (1.26) Male −17.04 ± (1.27)			
		Healthy Controls			**People with Multiple Sclerosis**		
Morrison 2022	Acceleration attenuation/gain measures whether the acceleration signal from the				−0.15 ± (0.39)	−0.43 ± (0.30)	−0.25 ± (0.13)

(*continued on next page*)

Table 5 (*continued*)

Study ID	Parameter computation	Shock absorption					
		Healthy subjects			Neurological Disorders		
		Antero-Posterior	Medio-Lateral	Vertical	Antero-Posterior	Medio-Lateral	Vertical
	trunk to the head gained (positive value) or attenuated (negative value).						
		Healthy controls			**People with Parkinson's Disease**		
Buckley 2015	Same approach proposed by Mazzà et al.	Cph 18.38 ± 24.85	Cph 33.8 ± 21.3	Cph −3.84 ± 7.68	Cph 12.53 ± 29.09	Cph 0.12 ± 34.7	Cph −3.23 ± 10.1
		Healthy controls			**People with Stroke**		
Bergamini 2017	Same approach proposed by Mazzà et al.	Cph [31.95–13.55] Csh [16.67–14.99]	Cph [18.40–9.22] Csh [−7.55–11.53]	Cph [−3.52–1.44] Csh [1.67–4.33]	SG1 Cph [−19.38–22.21] Csh [−96.94–54.21] SG2 Cph [1.10–35.75] Csh [−35.81–31.72] SG3 Cph [35.70–21.72] Csh [−12.75–21.92]	SG1 Cph [−5.25–21.34] Csh [−9.00–17.30] SG2 Cph [9.46–18.40] Csh [−8.71–10.09] SG3 Cph [9.75–26.81] Csh [−6.98–8.65]	SG1 Cph [1.10–11.52] Csh [−8.71–9.51] SG2 Cph [0.23–9.22] Csh [−1.79–7.21] SG3 Cph [4.84–8.65] Csh [2.83–5.76]

YG: Young Group; OG: Old Group; SS: Slow speed; PS: Preferred speed; FS: Fast speed; Data presentation: Mean ± Standard Deviation, Mean ± (Standard Error).

Table 6
JBI assessment for Cross-Sectional studies.

Study ID	1) Criteria for inclusion clearly defined	2) Study subjects and the setting described in detail	3) Exposure measured in a valid and reliable way	4) Objective, standard criteria used for measurement of the condition	5) Confounding factors identified	6) Strategies to deal with confounding factors stated	7) Outcomes measured in a valid and reliable way	8) Appropriate statistical analysis used
Brodie 2013	Y	Y	Y	Y	Y	Y	U	Y
Cromwell 2001a	Y	Y	Y	Y	Y	N	Y	Y
Cromwell 2001b & Cromwell 2004	Y	Y	Y	Y	Y	N	Y	Y
Hausamann 2019	Y	Y	Y	Y	N	N	Y	Y
Hausamann 2021	Y	Y	Y	Y	N	N	Y	Y
Kavanagh 2006	Y	Y	Y	Y	N	N	Y	Y
Latt 2007	Y	Y	Y	Y	Y	N	Y	Y
Morrison 2022	Y	Y	Y	Y	N	U	Y	Y
Nadeau 2003	Y	Y	Y	Y	Y	U	Y	Y
Pozzo 1989	Y	Y	Y	Y	U	U	Y	U
Pozzo 1990	Y	Y	Y	Y	U	U	Y	U
Thomas 2020	Y	Y	Y	Y	U	U	Y	Y
Thumser 2009	N	U	Y	Y	Y	Y	Y	U
Usumez 2006	Y	N	N	Y	N	N	N	Y

Y: Yes; N: No; U: Not reported or Unclear.

included, yet only a qualitative analysis was performed for the miscellaneous methodologies presented and the different outcomes considered. Nevertheless, this systematic review provides a comprehensive overview of the most common methodologies, settings, and outcome variables used to assess head movements, which is useful for planning future studies.

The studies consistently employed two key instruments for assessing head movements: optoelectronic systems and inertial measurement units (IMUs). Older studies predominantly relied on optoelectronic systems, while recent research has decisively shifted toward using IMUs. Notably, three studies effectively combined both instruments, demonstrating a comprehensive approach to movement analysis. The flexibility of IMUs in terms of settings, probe count, and cost supports their adoption. Moreover, IMUs, compared to the gold-standard method (i.e., an optoelectronic system), demonstrated good accuracy, as reported by Hausamann et al. (2021). Additionally, all studies, including those on PwMS, PwPD, and PwStroke, used IMUs to measure head movements, suggesting that these instruments may be a good choice for research or clinical applications.

The available movement analysis instruments must be chosen based on the study setting. This choice is critical; most included studies performed walking tests overground, and only one performed them on a

Table 7
JBI assessment for Case-Control studies.

Study ID	1) Groups comparable other than the presence of disease	2) Proper match between case and controls	3) Criteria used for identification of cases and controls	4) Exposure measured in a standard, valid and reliable way	5) Exposure measured in the same way for cases and controls	6) Confounding factors identified	7) Strategies to deal with confounding factors stated	8) Outcomes assessed in a standard, valid and reliable way	9) Exposure period of interest long enough	10) Appropriate statistical analysis used
Bergamini 2017	Y	Y	Y	Y	Y	Y	Y	Y	NA	y
Buckley 2015	Y	Y	Y	Y	Y	Y	Y	Y	NA	Y
Cattaneo 2005	Y	Y	N	Y	N	Y	Y	Y	NA	Y
Cole 2010	Y	Y	Y	Y	Y	Y	Y	Y	NA	Y
Cromwell 2002	Y	Y	Y	Y	Y	N	N	Y	Y	Y
Deshpande 2014	Y	Y	Y	Y	Y	N	N	Y	Y	Y
Hirasaki 1992	Y	Y	Y	Y	Y	Y	N	Y	Y	Y
Latt 2009	Y	Y	Y	Y	Y	Y	Y	Y	NA	Y
Maslievic 2017	Y	Y	Y	Y	Y	N	U	Y	NA	Y
Mazzà 2008	Y	Y	Y	Y	Y	Y	U	Y	NA	Y
Mazzà 2009	Y	Y	Y	Y	Y	Y	U	Y	NA	Y
Pelicioni 2018	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Psarakis 2018	Y	U	Y	Y	Y	U	U	Y	Y	Y

Y: Yes; N: No; U: Not reported or Unclear; NA: Not Applicable.

treadmill (Cattaneo et al., 2005). Gait speeds vary among studies. Generally, the most adopted speed is self-selected, while other frequently applied options are fast and slow gait. According to the studies, different gait speed conditions in HS do not appear to significantly alter most head movement outcomes (i.e., head angular displacement, head acceleration, harmonic ratio, and shock absorption) at walking speeds below 1.8–2 m/s. This result is also supported by Hirasaki et al. (Hirasaki et al., 1999). Therefore, in studies on HS, selecting a specific gait speed should be independent of the outcome but related to the study's aims. However, among people with neurological disorders, none of the included studies compared distinct gait speed conditions, as only self-selected speed was used. Further studies should verify possible speed-related differences. When comparing HS and people with neurological disorders (PwND), self-selected speed has been the most used measure to date and, consequently, provides a reliable basis for comparison. Moreover, the self-selected gait speeds of the healthy and pathological populations must be comparable to allow a reliable match. This method allows for consistent comparisons with results from previous studies, including those featured in this systematic review. Further studies should examine head movements at a set gait speed (e.g., using a treadmill) in a healthy population. However, studies involving populations with pathology appear to show an increase in head acceleration as walking ability decreases (Bergamini et al., 2017; Buckley et al., 2015; Morrison et al., 2022).

In terms of outcomes, head angular displacement is the one most commonly used for HS. Most included studies focused only on the sagittal plane (i.e., pitch movement), assessed in 10 studies, and results were consistent across them, with values ranging from 5° to 10°. Frontal and transverse planes showed less consistency, with only 2 studies conducted for each plane. Five studies computed head angular velocity for the sagittal plane, showing good consistency (e.g., values from 28 to 31°/s). Only two studies with low consistency were found in the frontal plane, and none examined head angular velocity in the transverse plane. Therefore, the current evidence on these planes must be strengthened through further research. However, no studies, including those involving people with neurological disorders, have measured head angular displacement or velocity. These parameters can play a crucial role in clinical and research settings.

Other head outcomes, such as shock absorption, harmonic ratio, and accelerations, were considered in all studies recruiting PwMS, PwPD, and PwStroke. These measures are helpful because they reflect the body's ability to absorb shocks and the consequent accelerations generated by walking (i.e., shock absorption and head accelerations), as well as the production of rhythmic acceleration patterns (i.e., harmonic ratio). Indeed, they serve as indicators of the efficacy of balance control mechanisms (Kavanagh et al., 2004), motor ability (Mazzà et al., 2008), and the ability to minimize gait metabolic costs (Ratcliffe and Holt, 1997). All these parameters are also of primary importance in studies of pathological subjects and, consequently, in a clinical setting. However, if the calculation methods for harmonic ratio and accelerations are clearly defined (Smidt et al., 1971), studies assessing shock absorption use heterogeneous methodologies for their computation, as shown in Table 5, which prevents comparison of the obtained results. Moreover, studies on head harmonic ratio and head accelerations remain limited. Consequently, defining a range of values for HS and for people with neurological disorders is complex. Nevertheless, even if future studies define a shared method for analyzing these parameters and allow comparisons across studies, including these outcomes in the assessment of people with neurological disorders is fundamental.

Another important factor that emerged from the critical appraisal of the studies is the lack of identification and management of potential confounding factors in many reports. Methodologically, most of the studies demonstrated a rigorous design, particularly in participant inclusion, assessment methods, and statistical analyses, although some issues were noted. For instance, none of the included studies calculated an *a priori* sample size, which could have strengthened the results. In addition, no one has registered their study protocol, which may increase the study's value, even if it is an observational study. Even given the biomechanical focus of included studies, the incomplete identification and management of confounding factors may be somewhat justified;

however, further studies should improve the critical analysis of their results.

This study presents several limitations; the included studies did not allow a quantitative analysis. Consequently, only a qualitative analysis was performed. However, this is the first study summarizing the literature on head movement analysis during unperturbed linear gait. Surprisingly, only seven studies included people with neurological disorders (2 studies on MS, four studies on PD, 1 study on Stroke) among their participants. Many studies on people with neurological disorders were excluded as they did not report data on head stability during unperturbed gait, as illustrated in the exclusion reasons provided in Fig. 1. This is unfortunate, since linear and unperturbed gait is one of the most frequently performed daily activities and one of the most frequently treated conditions during rehabilitation (Amatya et al., 2019).

This review could have clear translational implications for clinical rehabilitation practice, highlighting the importance of a common, shared assessment of HTS movement. Quantifying parameters such as head acceleration and harmonic ratio using portable IMUs enables the identification of HTS stabilization deficits in PwMS, PwPD, or PwStroke, guiding personalized interventions, such as biofeedback training, to curb oscillations and fall risk. Progressive neck-trunk stabilization protocols—from static to dynamic gait tasks—could optimize Vestibulo-Ocular Reflex control and shock absorption, yielding functional improvements.

The systematic review identified the significant parameters for analyzing head movements during gait. We recommend including unperturbed walking at a self-selected speed as one of the aims for future studies and assessing head motion using optoelectronic systems and/or IMUs. It is crucial to systematically include outcomes such as head angular displacements, shock absorption, the harmonic ratio of the head, and head accelerations to provide a multivariate assessment of the head and enable comparison of results across studies. They should be considered in research and clinical evaluation, even if the available evidence needs improvement.

CRediT authorship contribution statement

Joel Pollet: Writing – original draft, Investigation, Formal analysis. **Anna Di Meo:** Writing – review & editing, Investigation, Formal analysis. **Alessandro Torchio:** Writing – review & editing, Methodology, Data curation. **Fabiola Giovanna Mestanza Mattos:** Writing – review & editing, Methodology, Investigation. **Riccardo Buraschi:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Laura Bonzano:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Marco Bove:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Davide Cattaneo:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Elisa Gervasoni:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2026.113284.

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