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REVIEW

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Gait characteristics in idiopathic normal pressure hydrocephalus: a review on the effects of CSF tap test and shunt surgery

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Abstract

Background Idiopathic normal pressure hydrocephalus (iNPH) is a progressive disease characterized by disproportionate ventricular enlargement at brain imaging with gait disturbance and an increased risk of falling. Gait assessment is a key feature in the diagnosis of iNPH and characterization of post-surgical outcomes.

Research question How do gait parameters change 24 h after CSF tap test (CSFTT) and after ventriculoperitoneal shunt surgery?

Methods The PRISMA guidelines were used to perform the systematic review. We conducted a search of the following electronic databases: PubMed, Medline, Web of Science and EBSCO. We included studies focusing on gait changes occurring 24 h after a CSFTT or after ventriculoperitoneal shunt surgery in patients with iNPH. All articles were assessed for methodological quality using an adapted version of The Standard Quality Assessment Criteria for Evaluating Primary Research Papers checklist.

Results Twenty-seven studies were included in the systematic review. Studies were highly heterogeneous due to lack of standardization of CSFTT or shunt surgery methodology, with varying amounts of CSF removed during the tap test (20–50 ml) and varying time of outcome assessment after shunt surgery. Dynamic equilibrium measurements are generally used to assess preoperative levels of cardinal symptoms and postoperative outcomes in iNPH. The most sensitive spatio-temporal parameter assessed 24 h after CSFTT was self-selected walking speed followed by stride length, which increased significantly. Cadence is hence not suitable to consider in the evaluation of effect of CSFTT and shunt surgery. Changes in balance-related gait parameters after CSFTT and shunt surgery are still a controversial area of research.

Conclusion Gait assessment is a key feature in the diagnosis of iNPH and characterization of post-surgical outcomes. Dynamic equilibrium measurements are generally used to assess preoperative levels of cardinal symptoms and postoperative outcomes in iNPH, but quantitative and standardized gait analysis procedures are missing. Changes in balance-related gait parameters after CSFTT might be useful in deciding whether to perform shunt surgery in iNPH patients who hope for improvement in gait ability. The dual-task paradigm after CSFTT could improve the clinical evaluation of higher level frontal gait disturbances in patients with suspected iNPH before shunting.

Keywords Hydrocephalus, CSF tap test, Shunt, Gait analysis

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Introduction

Idiopathic normal pressure hydrocephalus (iNPH) is a progressive brain disease characterized by disproportionate ventricular enlargement seen on brain imaging. Evidence of ventricular enlargement (e.g., Evan's index ≥ 0.3 or equivalent) by brain imaging is necessary but not sufficient by itself to establish a diagnosis of iNPH. The syndrome is characterized by the Hakim–Adams triad of symptoms: progressive gait disturbance, cognitive deficit and urinary incontinence (described by Hakim and Adams in 1965) [1–3]. Symptoms are partially reversible after cerebrospinal fluid (CSF) drainage, which makes iNPH the leading cause of reversible dementia in aging. The treatment of iNPH consists in the surgical placement of a shunt. The CSF tap test (CSFTT), which consists in the removal of CSF through a lumbar puncture, is a common prognostic procedure for response to shunting.

Gait disturbance is usually the first symptom occurring in iNPH and is associated with an increased risk of falling, whereas cognitive impairment and urinary incontinence may occur at later stages [3]. Early detection of gait changes in iNPH combined with differential diagnosis from similar motor signs (iNPH mimicry) represents a crucial challenge for effective treatment in the prodromal stages of the disease [4].

In 1977, the neurologist Miller–Fisher comprehensively described gait changes in iNPH for the first time and used the term gait apraxia, which is still the generally accepted definition in the literature [5]. Although typical features of gait in iNPH are broad-based gait support with external rotation of foot posture, decreased gait speed, decreased stride length, prolonged duration of the period of double support, and poor foot-to-floor clearance, recent findings suggest that gait phenotypes are not specific in iNPH [5, 6]. Patients with iNPH have significant difficulty in turning on the body's long axis (multistep turns). Gait initiation failure or freezing are also evident [7]. Moreover, dynamic balance is also impaired in iNPH, including changes in the control of rhythmic stepping related to increased stride time and stride length variability, which leads to increased risk of falling during obstacle avoidance or on rough pathways [8, 9]. In addition, Knutsson and Lying-Tunell [10] reported that patients with iNPH have a reduced range of motion (ROM) in the sagittal plane at the hip, knee and ankle joints during gait. Kinematic analyses revealed that the reduced foot-to-floor clearance is due to the insufficient knee extension and forefoot dorsal extension at the end of the swing phase [11].

Comparing the prognostic impact of various techniques suggests that positive CSFTT, among the most widely used screening techniques for diagnosis of iNPH, add high sensitivity, but relative low specificity for shunt surgery response [12]. Gait assessment is another key feature in the diagnosis of iNPH and prediction of post-surgical outcomes. However, the clinical presentation requires further supportive evaluation for confirmation of iNPH diagnosis [13].

The aim of this study was to systematically review the literature investigating gait changes occurring 24 h after a CSFTT, or after ventriculoperitoneal (VP) shunt surgery.

Materials and methods

Search strategy

This systematic review was performed in May 2023 by two independent researchers (IH and AG) following the PRISMA (Preferred Reporting Items form Systematic Reviews and Meta-Analyses) guidelines [14]. The review and protocol was not registered. We conducted a search of the following electronic databases, with no date restrictions: PubMed, Medline, Web of Science and EBSCO, with the last search updated in January 2023. The following terms were used for databases search: (1) normal pressure hydrocephalus, (2) gait OR locomotion OR walking, (3) tap test OR shunt surgery. These search terms were combined: '(1) AND (2) AND (3)'.

Inclusion and exclusion criteria

Studies meeting the following PICOS criteria were included:

- Participants: patients with idiopathic normal pressure hydrocephalus.
- Interventions: gait assessment after a CSFTT or after VP shunt surgery.
- Comparator: gait assessment between baseline and 24 h after a CSFTT; gait assessment between baseline/post CSFTT and VP shunt surgery.
- Outcomes: dynamic equilibrium measurements, spatio-temporal parameters, kinematic and kinetic parameters.

The dynamic equilibrium measurements, spatio-temporal, kinematic and kinetic variables were evaluated to assess gait parameters in iNPH. Dynamic equilibrium measurements assess of dynamic balance function during gait (i.e., postural control during gait). They are useful for predicting falls and frontal higher-level gait disorder characterized by small step and disequilibrium gait in iNPH. Spatiotemporal (distance and time) variables concerning the foot step pattern include the step length, walking speed and cadence as well as the proportion of gait cycle time spent in double limb stance. The term kinematics refers to the pattern of movement. In the case of gait, it refers to variables such as the angular displacement of the hips, knees and ankle joints over time and the postural alignment of body segments throughout the gait cycle. Kinetics refers to the underlying forces, powers and energies of the lower limbs and trunk that enable the person to walk [15].

- Study types: peer-reviewed experimental trials

Exclusion criteria were (1) gait assessment after CSFTT at a time different from 24 h, (2) missing information on CSF extraction (ml) and time of gait analysis after CSFTT or shunt surgery, (3) external lumbar drainage or lumboperitoneal shunt surgery, (4) studies written in a language other than English. We discarded studies reporting gait assessment after lumboperitoneal shunt surgery because of the limited number of published work (see next section).

Study quality assessment

Two authors (IH, TD) conducted the methodological quality of each included study. Discrepancies were resolved through consensus among the authors. The Standard Quality Assessment Criteria for Evaluating Primary Research Papers checklist, developed by Kmet et al. [16], was used to assess the methodological quality of each included study. This checklist assesses 14 items, including study aims and design, recruitment and description of participants, sample size, outcome measures, data analysis, results, and conclusions. Studies were then categorized based on the following methodological quality index: 'high quality' for scores > 80%; 'good quality' for scores between 70 and 80%; 'average quality' for scores between 50 and 69%; and 'low quality' for scores below 50%.

Data extraction

Data extraction was performed manually by two researchers (IH, AG) and recorded in an Excel© sheet. Two authors performed data extraction individually; in case of disagreement, the third author was consulted. Data were then finalized and with the agreement of all authors. The following items were extracted from peer-reviewed experimental trials. Extracted variables included primary author, publication year, study design, clinical criteria for iNPH, exclusion criteria, number of participants and demographics, mean age ± standard deviation (SD), reports the amount of withdrawn CSF (ml), time of gait assessment after shunt surgery, methods of gait assessment, spatio-temporal parameters (mean ± standard deviation; *p* value, kinematic and kinetic parameters(mean ± standard deviation; *p* value).

Results

Final study selection

A total of 1475 studies were identified (see Fig. 1). Seven additional studies were found through the reference lists of included articles. After removal of duplicates, 765 articles remained. This was followed by a two-stage relevance analysis of the identified studies. In the first stage, we excluded 703 studies that were irrelevant to the inclusion and exclusion criteria based on title and abstract. In the next phase, 62 studies were assessed on the basis of full texts, with 7 full-text studies not found. In addition, 29 full texts were excluded due to wrong population ($n = 6$), time of gait assessment not found ($n = 3$), time of gait assessment after CSFTT different from 24 h ($n = 11$), type of the study different from original research, review, letter to the editor ($n = 2$), outcome parameters not respecting inclusion criteria ($n = 3$), use of external lumbar drainage ($n = 2$), use of lumboperitoneal shunt surgery ($n = 2$). After this screening procedure, 27 studies were included in the systematic review. The studies were divided according to gait assessment 24 h after CSFTT, or after VP shunt surgery. Two studies assessed gait changes both 24 h after CSFTT and after VP shunt surgery.

Methodological quality

Standard quality assessment criteria for the evaluation of original research articles are presented in Table 1. The methodological quality of 26 studies had a mean score of 85.9%. Studies were given an overall quality rating of ($n = 16$) good [7, 17–21, 23–26, 28, 29, 32, 34, 39, 41], ($n = 7$) average [30, 31, 33, 37, 38, 40], and ($n = 4$) low [22, 27, 35, 36]. All studies met the criterium 'sufficiently described question/objective?' (1). However, two studies [22, 30] did not have a 'study design evident and appropriate' (2). Six studies [27, 31, 36, 7, 37, 40] lacked a 'method of subject/comparison group selection or source of information/input variables described and appropriate' (3), and for three studies [34, 39] this description was partial. Studies were highly heterogeneous due to lack of standardization of CSFTT or shunt surgery methodology, with varying amounts of CSF removed during the tap test (20—50 ml), lack of standardization of outcome measures, and varying time of outcome assessment after CSFTT or shunt surgery [24]. Eight studies [7, 27, 31, 33–37, 40] did not adequately 'describe subject (and possibly comparison group) characteristics' (4). In particular, the main methodological problem was the lack of explicit inclusion and exclusion criteria for patients with iNPH. The following criteria were not listed or could not be determined for all studies: 'interventional and random

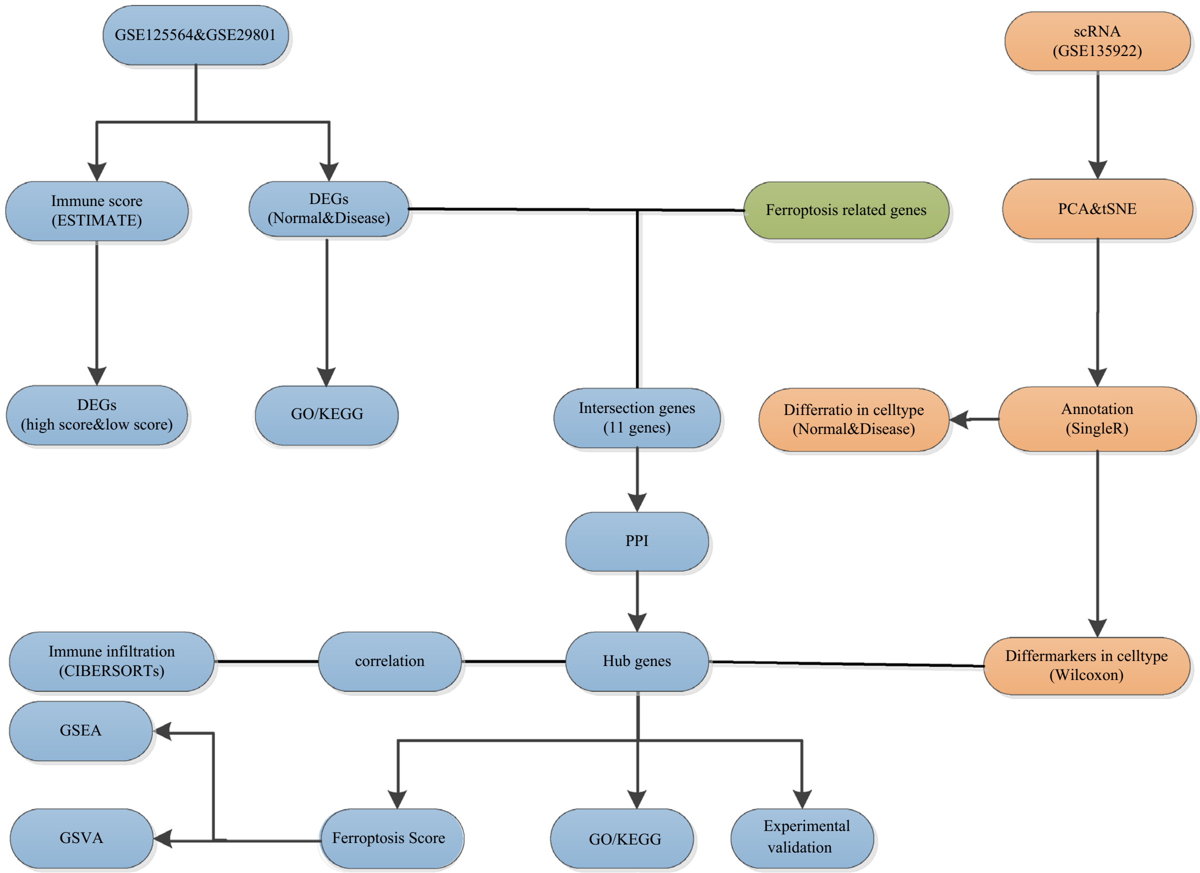

Fig. 1 PRISMA flow diagram of the systematic review. ELD: external lumbar drainage; LP: lumboperitoneal

allocation' (5); 'interventional and blinding of investigator' (6) or of 'subject' (7); 'sample size appropriate' (9); 'controlled for confounding' (12). One study [36] did not include information on the 'analytical methods' (10). Five studies [22, 23, 30, 35, 36] reported no 'estimate of variance for the main results' (11) and six studies [22, 23, 30, 32, 33, 35] did not report 'results in sufficient detail' (13). In particular, they relied on presenting results in tables where gait parameters were often not clearly described. All studies included 'conclusions supported by the results' (14). We summarized the general characteristic of included studies 24 h after CSFTT (Table 2) and after shunt surgery (Table 3). We collected the results obtained in the quoted studies that investigated changes in gait patterns occurring 24 h after a CSFTT (Table 4), or after VP shunt surgery (Table 5).

Dynamic equilibrium measurements 24 h after a CSFTT

The Timed Up-and-Go (TUG) test has been found to be most commonly used to assess functional performance and dynamic balance of gait at baseline and 24 h after the CSFTT [19–21, 24–26, 30, 31]. During TUG patients raised from a chair with armrests, walked 3 m forward, turned 180° around a traffic cone, walked 3 m backward and sat back on the same chair. The test was repeated three times in order to filter out the effect due to habituation or lack of attention. A significant decrease in TUG test time after CSFTT was demonstrated [19–21, 25, 30, 31]. The 18 m walk test provides another option for assessment, but no significant differences were found between baseline assessment and 24 h after the CSFTT [25, 27]. Bovonsunthonchai et al. [21] assessed significant decrease the sit-to-stand transfer time, the number of steps and no significant changes in turning time were found. Allali et al. [19] reported that patients experienced a significant decrease in TUG after CSFTT, (with a parallel trend toward decreased imaginary TUG time which, however, was not significant. Two studies [24, 26] comparing quantitative motor performance before, 24 and 72 h after CSFTT in iNPH reported that the best performance was recorded 72 h but not 24 h after the CSFTT, despite a progressive improvement in TUG [25, 27].

Table 1 Standard quality assessment criteria for evaluating primary research paper checklist

Study	Questions														Score (%)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Stolze et al., 2000 [17]	Y	Y	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	100
Schniepp et al., 2016 [18]	Y	Y	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	100
Marques et al., 2017 [19]	Y	Y	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	100
Allali et al., 2017 [20]	Y	Y	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	P	Y	94
Bovonsunthonchai et al., 2018 [21]	Y	Y	Y	P	n/a	n/a	n/a	Y	n/a	P	Y	n/a	Y	Y	89
Souza et al., 2018 [22]	Y	N	Y	Y	n/a	n/a	n/a	Y	n/a	Y	N	n/a	N	Y	67
Lim et al., 2019 [23]	Y	Y	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	N	Y	89
Giannini et al., 2019 [24]	Y	Y	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	100
Isik et al., 2019 [25]	Y	Y	Y	P	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	94
Ferrari et al., 2020 [26]	Y	Y	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	100
Sun et al., 2020 [27]	Y	Y	N	N	n/a	n/a	n/a	Y	n/a	Y	N	n/a	Y	Y	67
Griffa et al., 2020 [28]	Y	Y	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	100
Morel et al., 2021 [29]	Y	Y	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	100
Chunyan et al., 2021 [30]	Y	N	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	N	Y	78
Matsuoka et al., 2022 [31]	Y	Y	N	N	n/a	Y	n/a	Y	n/a	Y	N	n/a	Y	Y	70
Chen et al., 2018 [32]	Y	Y	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	N	Y	89
Nikaido et al., 2018 [33]	Y	Y	Y	N	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	N	Y	78
Kitade et al., 2018 [34]	Y	Y	P	Y	n/a	n/a	n/a	P	n/a	Y	Y	n/a	Y	Y	89
Song et al., 2018 [35]	Y	Y	Y	N	n/a	n/a	n/a	Y	n/a	Y	N	n/a	N	Y	67
Baltateanu et al., 2019 [36]	Y	Y	N	N	n/a	n/a	n/a	n/a	n/a	N	N	n/a	Y	Y	50
Sundström et al., 2022 [37]	Y	Y	N	N	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	78
Gago et al., 2022 [38]	Y	Y	N	Y	n/a	n/a	n/a	N	n/a	Y	Y	n/a	Y	Y	78
Hülser et al., 2022 [39]	Y	Y	P	P	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	89
Hallqvist et al., 2022 [40]	Y	Y	N	N	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	78
Ferrari et al., 2022 [7]	Y	Y	Y	N	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	89
Giannini et al., 2023 [41]	Y	Y	Y	Y	n/a	n/a	n/a	Y	n/a	Y	Y	n/a	Y	Y	100
Mean															85.9

Studies presented in chronological order. The question numbers of the standardized instrument standard quality assessment criteria for evaluating primary research paper checklist are as follows:

1 Question/objective sufficiently described?

2 Study design evident and appropriate?

3 Method of subject/comparison group selection or source of information/input variables described and appropriate?

4 Subject (and comparison group, if applicable) characteristics sufficiently described?

5 If interventional and random allocation was possible, was it described?

6 If interventional and blinding of investigators was possible, was it reported?

7 If interventional and blinding of subjects was possible, was it reported?

8 Outcome and (if applicable) exposure measure(s) well defined and robust to measurement/misclassification bias? Means of assessment reported?

9 Sample size appropriate?

10 Analytic methods described/justified and appropriate?

11 Some estimate of variance is reported for the main results?

12 Controlled for confounding?

13 Results reported in sufficient detail?

14 Conclusions supported by the results?

Y = yes; N = no; P = partial; n/a = not applicable

Y: yes (2 points); N: no (0 points); n/a: not applicable; P: partial (1 point)

Quantitative analysis of the effects of CSFTT on spatio-temporal and kinematic parameters of gait after 24 h

The most sensitive spatio-temporal parameters assessed 24 h after CSFTT were self-selected walking speed followed by stride length, which increased significantly [11, 18, 20, 22, 23, 28–30]. A smaller number of studies found improvements in stride time. However, stride time and

Table 2 General characteristic of included studies 24 h after CSFTT

Study	Study design	Number of participants and demographics	CSFTT (ml)	Clinical criteria for iNPH	Exclusion criteria
Stolze et al., 2000 [17]	Case control	10 (6M, 4F), 75.9 ± 6.3	30	Clinical criteria Hakim and Adams [1] - moderate to severe gait disorder - disturbed cognitive functions and urinary incontinence - enlargement of the lateral ventricles (assessed using the Evans Index [EI] > 0.3) on MRI in the absence of a moderate or severe cortical atrophy - microvascular lesions in the white matter were accepted only to a mild degree	Additional neurological disorders Orthopedic disorders interfering with gait
Schniepp et al., 2016 [18]	Observational prospective study	24 (7M, 17F), 76 ± 8	30–50	Adapted from Relkin criteria [42]: - at least 2 clinical signs of the Hakim triad including gait disorder and cognitive dysfunction - enlargement of the lateral ventricles (assessed using the Evans Index [EI] > 0.3) on MRI or CT - an opening CSF pressure < 15 cm H2O - exclusion of other differential diagnoses	Additional neurological disorders Orthopedic disorders interfering with gait
Marques et al., 2017 [19]	Observational retrospective study	68 (42M, 26F) 75.1 ± 6.2	40	Relkin criteria [42]: - specify parameters N/A	Secondary normal pressure hydrocephalus Acute medical illness in the past 3 months Orthopedic disorders interfering with gait CSFTT in the past 3 months A treatment change between both assessments Inability to walk a minimum of 15 m without assistance
Allali et al., 2017 [20]	Observational prospective study	68 (46M, 22F), 75.9 ± 7.4	40	Relkin criteria [42]: - enlargement of the lateral ventricles (assessed using the Evans Index [EI] > 0.3) on MRI or CT	N/A
Bovonsunthonchai et al., 2018 [21]	Observational prospective study	27 (16M 11F), 77.3 ± 6.9	30–50	Specific criteria: - Mori et al., [43] guidelines	No MRI evaluation Unable to undergo CSFTT

Table 2 (continued)

Study	Study design	Number of participants and demographics	CSFTT (ml)	Clinical criteria for iNPH	Exclusion criteria
Souza et al., 2018 [22]	Observational prospective study	25 (10M, 15F), 76.2 ± 5.8	30	Relkin criteria [42]: - specify parameters N/A	Possible and unlikely INPH Secondary normal pressure hydrocephalus Consequence of head trauma Intracerebral hemorrhage, and meningitis/encephalitis Serious clinical or laboratory contraindication for the procedure (blood dyscrasias not amenable to correction) Ventricular dilatation caused by macroscopic obstruction to CSF flow Severe cerebral atrophy Orthopedic disorders interfering with gait Musculoskeletal disorders (rheumatoid arthritis, polyneuropathy) Chronic obstructive pulmonary disease and/or heart failure with dyspnea on minimal exertion Other causes of dementia
Lim et al., 2019 [23]	Observational prospective study	23 (11M, 12F), 73.0 ± 7.2	30–50	Relkin criteria [42]: - specify parameters N/A	Additional neurological disorders Orthopedic disorders interfering with gait Psychiatric disorder Metabolic or neoplastic disorders Dementia symptoms or parkinsonism Recent history of heavy alcohol use
Giannini et al., 2019 [24]	Observational prospective study	35 (20M, 15F) 71.87 ± 5.66	30–50	Specific criteria: - The Bologna PRO-Hydro study	Severe psychiatric disease Alcohol or drugs addiction Serious ongoing physical illness Inability to sign the informed consent
Isik et al., 2019 [25]	Observational retrospective study	42 (17M, 25F) 79.1 ± 6.9	30	Relkin criteria [42]: - specify parameters N/A	Secondary normal pressure hydrocephalus Thrombocytopenia (< 50.000) Refusal by the patient (technical difficulty for lumbar puncture) Incapable of understanding the commands required to do a certain task Inability to walk
Ferrari et al., 2020 [26]	Observational prospective study	56 (31M, 25F), 74 ± 5.1	30–40	Relkin criteria [42]: - specify parameters N/A	Presence of severe psychiatric disease or physical illness Addiction to drugs
Sun et al., 2022 [27]		6 (6M, 0F), 77.7 ± 5.4	20–40	N/A	N/A

Table 2 (continued)

Study	Study design	Number of participants and demographics	CSFTT (ml)	Clinical criteria for iNPH	Exclusion criteria
Griffa et al., 2020 [28]	Observational prospective study	26 (14M, 12F) 79.7 ± 6.3	40	Relkin criteria [42]: - specify parameters N/A	Secondary normal pressure hydrocephalus Acute medical illness in the past 3 months Orthopedic disorders interfering with gait
Morel et al., 2021 [29]	Observational retrospective study	77 (52M, 25F), 76.1 ± 6.2	40	Relkin criteria [42]: - specify parameters N/A	Secondary normal pressure hydrocephalus Acute medical illness in the past 3 months
Chunyan et al., 2021 [30]	Observational prospective study	26 (17M, 9F), 72 ± 6	30	Specific criteria: - Mori et al., [43] guidelines	Secondary normal pressure hydrocephalus Inability to walk Unable to ambulate the procedure
Matsuoka et al., 2022 [31]	Observational retrospective study	29 (15M, 14F), 77.5 ± 7.3	30	N/A	Secondary normal pressure hydrocephalus Delirium during the CSFTT Orthopedic disorders interfering with gait

The second column reports study design. The third column reports cohorts' demographics, including the number of male (M) and female (F) participants and the mean age (years). The fourth column reports the amount of withdrawn CSF (ml)

stride length variability contribute to the controversy in the assessment of CSFTT effects [20, 23, 27, 28]. There is no consensus on the changes in cadence and double support time parameters 24 h after CSFTT, despite numerous case studies [17, 22–24, 26, 27]. In addition, no study was found that objectified a single support time [17, 23, 27]. Moreover, none of the so-called balance-related gait parameters (stride width, step height, joint angle excursions) clearly changed 24 h after CSFTT [17, 20, 22, 23, 28].

The most frequently investigated spatio-temporal parameter evaluating the effect of the CSFTT was the self-selected walking speed, which was increased in most cases [11, 16, 18, 20, 22, 23, 28–31]. Frontal gait was significantly associated with walking speed improvement after CSFTT, even after adjusting on age, gender, comorbidities, white matter changes, and MMSE, as described by Morel et al. [29]. Frontal gait was defined by short steps, a wide base of support, and a magnetic component (reduced step height) evaluated by video analysis [43]. Only two studies reported no significant changes in walking speed after CSFTT. Giannini et al. [24] did not confirm changes in walking speed in the 18 m walk test or TUG at 24 h after CSFTT, whereas at 72 h the changes were statistically significant.

Another important spatio-temporal parameter that has been evaluated is the stride length, which increased with increasing walking speed 24 h after CSFTT [17, 22–24, 26, 28, 30]. Chunyan et al. [30] reported that stride length as measured by instrumented gait analysis increased significantly during the. Step length measured using an optoelectronic measurement system was significantly extended [28]. In contrast, two studies reported no change in step length 24 h after CSFTT [24, 26]. Ferrari et al. [26] found an improvement in stride length 24 h after CSFTT for the 18 m walk test, but not for the TUG test. Giannini et al. [24] reported that the TUG test time in iNPH was not significantly associated with the stride length.

Four studies evaluated the stride time before and 24 h after CSFTT [20, 23, 27, 28]. Allali et al. [20] reported a significant reduction in stride time measured by an optoelectronic measurement system. Similar findings were reported by Griffa et al. [28]. Lim et al. [23] used a computerized, 5.8 m-long, pressure-sensitive carpet system (GAITRite, CIR System) with a sampling rate of 120 Hz to improve the assessment of the stride time and stride length variability as assessed by the coefficient of variation (CV). They reported decreased CV after CSFTT for CV of stride time, and for CV of stride length. Sun et al. [27] reported that although stride time CV had some variation, it did not show significant changes. However, it should be noted that their analysis based on plantar pressure assessment did not highlight any changes in spatio-temporal gait parameters 24 h after CSFTT compared to baseline [27].

Six studies [17, 22–24, 26, 27] compared cadence (i.e., number of steps per minute) between baseline and 24 h after CSFTT. Three studies reported that cadence remained unchanged [11, 24, 27]. Souza et al. [22]

Table 3 General characteristic of included studies after VP shunt surgery

Study	Study design	Number of participants and demographics	Time of gait assessment after shunt surgery	Clinical criteria for iNPH	Exclusion criteria
Chen et al., 2018 [32]	Observational prospective study	18 (10M 8F), 70 ± 3.1	3 months	N/A	Age under 40 Asymmetrical or transient symptoms Cortical deficits (e.g. aphasia, apraxia or paresis) Dementia without gait disturbance Patients with CSF proteomic analyses showing increases in Alzheimer's disease related protein concentrations of p-tau, t-tau, and Aβ42 Brain CT showing marked dilatation of sulci and fissures, and poor visual distinction between grey and white matters that may indicate dementia
Nikaido et al., 2018 [33]	Observational prospective study	23 (19M, 4F), 76.9 ± 5.7	1 week	Specific criteria: - Mori et al. [43], guidelines	Additional neurological Orthopedic disorders interfering with gait Inability to walk unassisted for at least 15 m
Kitade et al., 2018 [34]	Observational prospective study	12 (5M 7F), 76.3 ± 4.6	± 19.5 days	Clinical criteria Hakim and Adams [1] - specify parameters N/A	History of major injuries of the lower extremities Surgery to either or both lower extremities Osteoarthritis of the lower extremities Other spinal disorder Cerebrovascular lesions Inability to walk 10 m without aids
Song et al., 2019 [35]	Observational prospective study	28 (16M, 12F), 75.2 ± 7.3	6 month	Specific criteria: - Marmarou et. al. [44]	Dementia, Parkinson's disease Stroke Uncontrolled medical comorbidities Diabetic or idiopatic peripheral neuropathy Alcoholism Lack of improvement from the CSFTT
Giannini et al., 2019 [24]	Observational prospective study	35 (20M, 15F) 71.87 ± 5.66	6 months	Specific criteria: - The Bologna PRO-Hydro study	Severe psychiatric disease Alcohol or drugs addiction Serious ongoing physical illness Inability to sign the informed consent
Baltateanu et al., 2019 [36]	Observational retrospective study	19 (12M 7F) 69.6 ± N/A	1 month	N/A	N/A
Sun et al., 2022 [26]		6 (6M, 0F), 77.7 ± 5.4	1 month	N/A	N/A
Sundström et al., 2022 [37]	Observational retrospective study	1249 (744, M 505F) 74.7 ± 6.0	3 months	Relkin criteria [42]: - specify parameters N/A	More than 80 s or steps in TUG (median TUG time + 4 × interquartile range)

Table 3 (continued)

Study	Study design	Number of participants and demographics	Time of gait assessment after shunt surgery	Clinical criteria for iNPH	Exclusion criteria
Gago et al., 2022 [38]	Observational prospective study	8 (4M 4F), 73.0 ± N/A	3–18 months	Relkin criteria [42]: - specify parameters N/A	Additional neurological disorders Orthopedic or rheumatologic disorders interfering with gait Inability to walk without aids
Hülser et al., 2022 [39]	Observational prospective study	30 (17M 13F), 76,9 ± 5.6	12 weeks	N/A	N/A
Matsuoka et al., 2022 [31]	Observational retrospective study	29 (15M, 14F), 77.5 ± 7.3	2 weeks	N/A	Secondary normal pressure hydrocephalus Delirium during the CSFTT Orthopedic disorders interfering with gait
Hallqvist et al. 2022 [40]	Observational retrospective study	118 (66M 52F), 73.5 ± N/A	3 months	N/A	Lacked results of gait pre- and postoperative
Ferrari et al., 2022 [7]	Observational cohort study	42 (15M, 27F) 75.2 ± 4.0	± 121 days	N/A	Addiction to drugs Severe psychiatric diseases or physical illness Clinical history possibly causing ventricular dilation
Giannini et al., 2023 [41]	Observational prospective study	64 (37M 28F), 75 ± N/A	6 months	Relkin criteria [42]: - specify parameters N/A	Partial clinical assessment Lacking appropriate neuroimaging

The second column reports study design. The third column reports cohorts' demographics, including the number of male (M) and female (F) participants and the mean age (years). The fourth column reports the time of gait assessment after shunt surgery

showed that the most sensitive parameter assessed after CSFTT was walking speed, followed by cadence which decreased significantly. Ferrari et al. [26], confirmed that a statistically significant improvement in cadence was found at both 24 h and 72 h) after CSFTT. However, the cadence during the 18 m walk test was increased 24 h but not 72 h after CSFTT [26]. In contrast, Lim et al. [23] confirmed a significant increase in cadence.

The greatest improvement in the gait parameters of iNPH patients after tapping 30 ml CSF was found for the walking speed (an average increase of 23.9%), followed by stride length (an increase of 20.9%), the double-limb support phase (a decrease of 16.4%), the stance phase (a decrease of 8.9%), and the swing phase of the gait cycle (an increase of 6.9%) [17]. Ferrari et al. [26] reported that double support time showed high statistical significance in TUG test and 18 m walk test., However, 2 studies [23, 27] reported no significant changes during double support.

Five studies compared kinematics between baseline and 24 h after CSFTT [17, 20, 22, 23, 28]. Stolze et al. [17] reported that none of the so-called balance-related gait parameters (stride width, step height, joint angle excursions) clearly altered in iNPH, responded to CSFTT during treadmill locomotion. Hip marks were often masked (exact data were available for 5 patients only), and therefore statistical tests for kinematic changes were not calculated after tapping of the hip joint in these patients. Ankle joint motion in the frontal plane (toe-in/toe-out angle) did not confirm any significant change [22, 23].

No change in step width was supported by highly objective studies that used an optoelectronic system with 12 cameras to record the trajectory of the reflective markers [20, 28]. A single study by Lim et al. [23] demonstrated that step width measured by the pressure-sensitive GAITRite carpet system decreased significantly. Allali el al. [20] and Souza et al. [22] observed that step height was the only gait parameter related to balance that increased significantly between baseline and 24 h after CSFTT.

The Geneva's protocol [20] reported mean values and coefficient of variability of spatio-temporal gait parameters as gait speed, stride time, stride width and heel height while the four dual-tasks (forward counting, backward counting, semantic fluency, phonemic fluency) after

Table 4 Evaluation of gait parameters 24 h after CSFTT

Study	Methods of gait assessment	Functional gait tests (mean ± standard deviation; *p* value)	Spatio-temporal parameters (mean ± standard deviation; *p* value)	Kinematic/kinetic parameters (mean ± standard deviation; *p* value)
Stolze et al., 2000 [16]	Treadmill	–	↑ Speed (23.9%), $p < 0.001$ ↑ Stride length (20.9%) $p < 0.001$ ↓ Single support time (8.9%), $p < 0.01$ ↓ Double support time (16.4%), $p < 0.01$ ↑ Swing phase time (6.9%), $p < 0.05$ No changes in cadence $p = NS$	No changes in step width, toe in/out angle $p = NS$ No changes ROM (hip, knee, ankle in the sagittal plane) $p = NS$
Schniepp et al., 2016 [17]	Pressure-sensitive carpet system GAITRite	–	↑ Comfortable speed Pre-post CSFTT: 0.59 ± 0.09–0.72 ± 0.11 m/s; $p < 0.020$ No changes in maximum speed Pre-post CSFTT: 0.93 ± 0.20–1.00 ± 0.19 m/s $p = NS$	–
Marques et al., 2017 [18]	Instrumented gait analysis	↓ Time score TUG Pre-post CSFTT: 29.62 ± 3.33–21.96 ± 2.20 s; $p < 0.01$	–	–
Allali et al., 2017 [19]	Optoelectronic motion system	↓ Time score TUG Pre-post CSFTT: 28.21 ± 35.0–27.66 ± 37.84; $p < 0.01$	↑ Speed—Pre-post CSFTT: 0.74 ± 0.28 m/s- 0.82 ± 0.29 m/s; p < 0.001 ↓ Stride time—Pre-post CSFTT: 1.25 ± 0.27–1.19 ± 0.17s; $p < 0.01$	No changes in step width pre-post CSFTT: 0.11 ± 0.05–0.10 ± 0.05 m; $p = NA$ ↑ Step height pre-post CSFTT: 0.18 ± 0.05–0.19 ± 0.05 m; $p < 0.001$
Bovonsunthonchai et al., 2018 [20]	Force distribution measurement platform	↓Time score TUG pre-post CSFTT: 15.49 ± 12.48–12.04 ± 6.58 s; $p < 0.048$ ↓Sit to stand time pre-post CSFTT: 5.58 ± 2.99–5.06 ± 2.91 s; $p < 0.046$ No changes in turning time Pre-post CSFTT: 7.53 ± 4.86 6.64 ± 3.66 s; $p < 0.064$ ↓ Turning step (number) Pre-post CSFTT: 8.61 ± 3.11 7.59 ± 2.39; $p < 0.001$	–	–
Souza et al., 2018 [21]	Instrumented gait analysis	–	↑ Speed pre-post CSFTT: 45.3 s–35.2 s (20 m); $p < 0.01$ ↑ Stride length; $p < 0.01$ ↑ Cadence; $p < 0.01$	No changes in toe in/out angle ($p = 1.0$), step width ($p = 1.0$) ↑ Step height ($p < 0.01$)

Table 4 (continued)

Study	Methods of gait assessment	Functional gait tests (mean ± standard deviation; *p* value)	Spatio-temporal parameters (mean ± standard deviation; *p* value)	Kinematic/kinetic parameters (mean ± standard deviation; *p* value)
Lim et al., 2019 [22]	Pressure-sensitive carpet system GAITRite	–	↑ Speed, pre-post CSFTT: 55.12 ± 4.81–67.84 ± 5.01 cm/s; $p < 0.01$ ↑ Stride length, pre-post CSFTT: 62.76 ± 5.14–72.38 ± 5.11 cm; $p < 0.05$ ↑ Cadence pre-post CSFTT: 105.33 ± 3.56–112.99 ± 3.40 steps/min; $p < 0.05$ ↓ Stride time, pre-post CSFTT: 1.17 ± 0.04–1.09 ± 0.04 s; $p < 0.05$ ↓Variability in stride time, pre-post CSFTT: 10.47 ± 2.27–6.05 ± 0.79%; $p < 0.05$ ↓Variability in stride length, pre-post CSFTT: 14.35 ± 1.98–9.44 ± 0.82%; $p < 0.01$ No changes in single support time Pre-post CSFTT: 67.81 ± 0.59–67.28 ± 0.93% No changes in double support time Pre-post CSFTT: 36.49 ± 1.34–34.81 ± 1.90% No changes in swing phase time Pre-post CSFTT: 32.19 ± 0.59 32.71 ± 0.93%	No changes toe in/out angle Pre-post CSFTT: 15.28 ± 1.65–14.57 ± 1.51° ↓ Step width Pre-post CSFTT: 13.57 ± 0.57–12.90 ± 0.60 cm; $p < 0.05$
Giannini et al., 2019 [23]	Instrumented gait analysis	No changes in time score TUG pre-post CSFTT: 22.28 ± 12.86–20.23 ± 8.38 s 18MWT pre-post CSFTT: 31.28 ± 14.90–28.71 ± 10.33 s	No changes in speed TUG/18MWT pre-post CSFTT: 52.53 ± 20.24–57.17 ± 19.04 cm/s 75.84 ± 22.48–80.65 ± 22.70 cm/s No changes in stride length TUG, 18MWT Pre-post CSFTT: 63.89 ± 21.79–65.07 ± 19.32 cm; 88.66 ± 22.61–90.24 ± 20.55 cm No changes in cadence TUG/18MWT pre-post CSFTT: 48.30 ± 8.76–50.84 ± 10.49 steps/min/50.81 ± 7.97–52.13 ± 6.85 steps/min	–
Isik et al., 2019 [24]	Instrumented gait analysis	↓ Time score TUG pre-post CSFTT: 23.3 ± 15.1–18.8 ± 9.8 s; $p < 0.001$	–	–

Table 4 (continued)

Study	Methods of gait assessment	Functional gait tests (mean ± standard deviation; *p* value)	Spatio-temporal parameters (mean ± standard deviation; *p* value)	Kinematic/kinetic parameters (mean ± standard deviation; *p* value)
Ferrari et al., 2020 [25]	Inertial sensors mGAIT	No changes in time score (TUG, 18MWT) $p < 0.190$, $p < 0.108$	TUG—No changes in stride length $p < 0.878$, ↑ Cadence $p < 0.009$, ↓ Double support time $p < 0.000$ 18MWT- ↑ Stride length $p < 0.023$, ↑ Cadence $p < 0.000$ ↓ Double support time $p < 0.000$	–
Sun et al., 2020 [26]	Plantar pressure-based temporal analysis (Podomed)	–	No changes in speed, pre-post CSFTT: 0.46 ± 0.20–0.54 ± 0.22 m/s; $p < 0.310$ No changes in cadence, pre-post CSFTT: 102.29 ± 14.87–103.78 ± 16.02 step/min; $p < 0.690$ No changes in stride time pre-post CSFTT: 1.21 ± 0.19–1.18 ± 0.19 s; $p < 0.690$ No changes in single support time Pre-post CSFTT: 63.84 ± 1.40–58.66 ± 1.77%; $p = 0.151$ No changes in double support time Pre-post CSFTT: 31.37 ± 3.80–30.42 ± 3.54%; $p = 0.310$	–
Griffa et al., 2020 [27]	Optoelectronic motion system	–	↑ Speed, pre-post CSFTT: 0.71 ± 0.26–0.79 ± 0.31 m/s; $p < 0.013$ ↑ Step length, pre-post CSFTT: 0.87 ± 0.26–0.91 ± 0.30 m; $p < 0.007$ ↑ Stride time, pre-post CSFTT: 1.25 ± 0.18–1.19 ± 0.18 m; $p < 0.042$	No changes in step width Pre-post CSFTT: 0.10 ± 0.03–0.11 ± 0.04 m; $p = 0.44$
Morel et al., 2021 [28]	Optoelectronic motion system (Vicon Mx3 +)	–	↑ Speed in frontal gait, pre-post CSFTT–delta: 0.51 ± 0.21—0.31 ± 0.31 m/s; $p < 0.001$	–
Chunyan et al., 2021 [29]	Instrumented gait analysis	↓Time score TUG Pre-post CSFTT: 21.9 ± 7.1–17.6 ± 5.1 s; $p < 0.001$ No changes time score 10MWT Pre-post CSFTT: 17.7 ± 7.7–17.2 ± 18.1 s; *p*: 0.829	↑ Speed, pre-post CSFTT: 0.7 ± 0.2–0.8 ± 0.3 m/s; $p < 0.001$ ↑ Stride length, pre-post CSFTT: 0.4 ± 0.1–0.46 ± 0.1 m/step; $p < 0.001$ No changes in cadence, pre-post CSFTT: 1.8 ± 0.3–1.7 ± 0.4 step/s; $p = 0.441$	–

Table 4 (continued)

Study	Methods of gait assessment	Functional gait tests (mean ± standard deviation; *p* value)	Spatio-temporal parameters (mean ± standard deviation; *p* value)	Kinematic/kinetic parameters (mean ± standard deviation; *p* value)
Matsuoka et al., 2022 [30]	Instrumented gait analysis	↓ Time score (TUG) Pre-post CSFTT: 25.5 ± 17.5–18.4 ± 13.6 s; $p < 0.000$ ↓ Time score (10 MWT comf./max.) Pre-post CSFTT: 22.4 ± 12.9–15.8 ± 8.7/20.6 ± 15.7–14.2 ± 9.1 s; $p < 0.001$/$p < 0.003$ ↓ Step count (10 MWT comf./max.) Pre-post CSFTT: 35.3 ± 17.1–27.5 ± 11.9/35.6 ± 23.8–26.1 ± 15.1; $p < 0.001$/$p < 0.003$	–	–

Table 5 Evaluation of gait parameters after VP shunt surgery

Study	Methods of gait assessment	Functional gait tests (mean ± standard deviation; *p* value)	Spatio-temporal parameters (mean ± standard deviation; *p* value)	Kinematic/kinetic parameters (mean ± standard deviation; *p* value)
Chen et al., 2018 [31]	Optoelectronic motion analysis system (Vicon 370)	–	No changes in speed L/R Before-after shunt: 0.34 ± 0.11/0.35 ± 0.13– 0.35 ± 0.13/0.34 ± 0.13 m/s ↓ Cadence L/R Before-after shunt: 129.93 ± 9.87/126.12 ± 7.45–99.40 ± 3.71 99.92 ± 3.81 steps/min; $p < 0.05$ ↑ Stride length L/R Before-after shunt: 0.10 ± 0.02/ 0.11 ± 0.03–0.20 ± 0.07/ 0.20 ± 0.08 m; $p < 0.05$ ↑ Single support time L/R Before-after shunt: 35.66 ± 5.27/ 35.24 ± 5.09–42.47 ± 4.22/ 41.54 ± 4.11%; $p < 0.05$ ↓ Double support time L/R Before-after shunt (%): 32.61 ± 3.12/ 32.41 ± 2.98–26.55 ± 2.98/26.16 ± 2.55%; $p < 0.05$	–
Nikaido et al., 2018 [32]	Triaxial accelerometer	–	↑ Speed SMD: 0.58 (95% CI: [− 0.24–− 0.09] m/s; $p = 0.004$ ↓ Step count SMD: 0.51 (95% CI: [3.77–12.34] step; $p = 0.010$ ↓ Stride time SMD: 0.66 (95% CI: [0.01–0.05] s; $p = 0.008$ ↓Variability in stride time SMD: 0.88 (95% CI: [2.59–7.60] %; $p < 0.001$	− 7.66 s (95% C.I. [− 9.47, − 6.09] s, mean before-after shunt: 24.07–16.41 s); $p < 0.05$ -

Table 5 (continued)

Study	Methods of gait assessment	Functional gait tests (mean ± standard deviation; *p* value)	Spatio-temporal parameters (mean ± standard deviation; *p* value)	Kinematic/kinetic parameters (mean ± standard deviation; *p* value)
Kitade et al., 2018 [33]	Optoelectronic motion analysis system (Vicon MX)	–	↑ Speed 0.45 ± 0.19–0.65 ± 0.22 m/s; $p < 0.001$ ↑ Stride length 0.27 ± 0.12–0.40 ± 0.13 m; $p < 0.001$ ↑ Cadence 99.9 ± 11.1–110.2 ± 11.0 steps/min; $p < 0.05$	↑ ROM in the sagittal plane Hip 28.5 ± 8.9–31.7 ± 8.0°; $p < 0.01$ Knee 35.5 ± 13.2–39.4 ± 10.2°; $p < 0.05$ Ankle 18.3 ± 5.5–22.7 ± 6.3°; $p < 0.001$ ↑Hip extension angle before-after shunt: − 0.41 ± 0.34–− 0.59 ± 0.50 Nm/kg; $p < 0.01$ ↑ Peak absorption power of the hip (terminal stance phase) − 0.2 ± 0.3–− 0.4 ± 0.4 W/kg; $p < 0.01$ ↑ Peak flexion moment of the hip (pre-swing phase) before-after shunt: − 0.41 ± 0.34–− 0.59 ± 0.50 Nm/kg; $p < 0.01$ Ankle (flat foot phase) before-after shunt: 0.8 ± 6.9–− 3.4 ± 5.5°; $p < 0.001$ ↑Peak generation power before-after shunt: Hip 0.3 ± 0.3–0.5 ± 0.6 W/kg; $p < 0.05$ Ankle 0.9 ± 0.9 W/kg–1.4 ± 1.3 W/kg, $p < 0.05$ ↑Peak absorption power of the knee (pre-swing phase) before-after shunt: − 0.4 ± 0.5–− 0.7 ± 0.7 W/kg; $p < 0.05$ No change in peak extension moment of the knee (Pre-swing phase) before-after shunt: 43.9 ± 12.0–44.1 ± 12.7°; $p = 0.93$
Song et al., 2019 [34]	ProtoKinetics Zeno walkway	No changes in time score (TUG, 25 walkway) $p = 0.0868$, $p = 0.1067$	↑ Speed (cm/s) Average difference 15.6660; $p < 0.0001$ ↑ Stride length (cm) Average difference 15.0531; $p < 0.0001$ ↑ Single support time (%) Average difference 1.4096; $p < 0.0001$ ↑ Swing phase time (%) Average difference 3.9922; $p = 0.0136$ No changes in cadence (steps/min) Average difference 0.7683; $p = 0.3524$	No changes in toe in/out angle (°) Average difference −0.8190; $p = 0.9166$ No change in step width (cm) Average difference 1.3353; $p = 0.4247$

Table 5 (continued)

Study	Methods of gait assessment	Functional gait tests (mean ± standard deviation; *p* value)	Spatio-temporal parameters (mean ± standard deviation; *p* value)	Kinematic/kinetic parameters (mean ± standard deviation; *p* value)
Giannini et al., 2019 [23]	Instrumented gait analysis	Before-after shunt: ↓ Time score (18 MWT) 31.28 ± 14.90–27.18 ± 11.43 s; $p = 0.0008$ ↓ Step count (18 MWT) 39.91 ± 16.51–35.03 ± 9.19 steps; $p = 0.0146$ ↓ Time score (TUG) 22.28 ± 12.86–15.21 ± 4.45 s; $p = 0.0034$ ↓ Step count (TUG) 25.03 ± 10.78—18.21 ± 4.70 steps; $p = 0.0093$ No changes in turn steps (TUG) 2.44 ± 1.48–1.85 ± 0.56 step; $p = 0.0757$	↑ Speed (TUG) 52.53 ± 20.24–62.67 ± 18.68 cm/s; $p < 0.0001$ ↑ Stride length (TUG) 63.89 ± 21.79–77.55 ± 16.59 cm; $p < 0.0001$ ↑ Cadence (TUG) 48.30 ± 8.76–52.17 ± 7.66 steps/min; $p = 0.0219$ ↑ Speed (18MWT) 75.84 ± 22.48–84.61 ± 23.06 cm/s; $p < 0.0001$ ↑ Stride length (18MWT) 88.66 ± 22.61–97.87 ± 22.17 cm; $p = 0.0086$ No changes in cadence (18MWT) 50.81 ± 7.97–53.36 ± 6.54 steps/min; $p = 0.0694$	–
Baltateanu et al., 2019 [35]	Instrumented Gait Analysis	↓ Time score (TUG) 37.68–24.42 s	↑ Speed (10 MWT) 523–734 mm/s	–
Sun et al., 2020 [26]	Plantar pressure-based temporal analysis (Podomed)	–	No changes before-after shunt: Speed 0.46 ± 0.20–0.57 ± 0.25 m/s; $p = 0.421$ Cadence 102.29 ± 14.87–107.68 ± 15.41 steps/min; $p = 1.000$ Stride time 1.21 ± 0.19–1.13 ± 0.15 s; $p = 0.841$ Single support time 66.59 ± 3.02–69.79 ± 4.47%; $p = 0.222$ Double support time 30.57 ± 6.19–29.23 ± 5.51%; $p = 0.421$	–
Sundström et al., 2022 [36]	Instrumented gait analysis	↓ Time score (TUG) before-after shunt: 22.2 ± 12.1–16.9 ± 9.2 s; $p < 0.001$ ↓ Time score (10 MWT) before-after shunt: 16.8 ± 9.8–13.1 ± 5.9 s; $p < 0.001$	–	–
Gago et al., 2022 [37]	Inertial sensors Physilog®	–	↑ Speed before-after shunt: 0.60 ± 0.28–0.82 ± 0.24 m/s; $p < 0.028$ ↑ Stride length before-after shunt: 0.66 ± 0.27–0.89 ± 0.25 m; $p < 0.027$ No changes in double support time Before-after shunt: 33.77 ± 10.62–26.97 ± 5.83%; $p = 0.107$	–

Table 5 (continued)

Study	Methods of gait assessment	Functional gait tests (mean ± standard deviation; *p* value)	Spatio-temporal parameters (mean ± standard deviation; *p* value)	Kinematic/kinetic parameters (mean ± standard deviation; *p* value)
Hülser et al., 2022 [38]	Instrumented gait analysis	↓ Time score (10 MWT) Before-after shunt:17.1 ± 7.5–11.9 ± 5.1 s; $p < 0.009$ ↓ Step count (10 MWT) Before-after shunt: 25.0 ± 6.4–18.5 ± 5.6 steps; $p < 0.001$	–	–
Matsuoka et al., 2022 [30]	Instrumented gait analysis	↓ Time score (TUG) Before-after shunt: 25.5 ± 17.5–18.2 ± 12.8 s; $p < 0.007$ ↓ Time score (10 MWT comf./max.) Before-after shunt: 22.4 ± 12.9–16.3 ± 10.1/20.6 ± 15.7–14.4 ± 9.7 s; $p < 0.000$/$p < 0.024$ ↓ Step count (10 MWT comf./max.) Before-after shunt: 35.3 ± 17.1–28.5 ± 16.0/5.6 ± 23.8–27.3 ± 16.1 s; $p < 0.002$/$p < 0.035$	–	–
Hallqvist et al. 2022 [39]	Instrumented gait analysis	↓ Time score (TUG) Before-after shunt:19 (7.2–187)–15.25 (7.6–128) s; $p < 0.0001$ ↓ Step count (TUG) Before-after shunt: 23 (12–210)–21 (13–100) steps; $p < 0.0001$	↑ Speed (10 MWT) Before-after shunt: 0.72 (0.1–1.33)–0.9 (0.25–1.49) m/s; $p < 0.0001$	–
Ferrari et al., 2022 [40]	Inertial sensors mGAIT	↓Time score TUG − 7.66 (95% C.I. [− 9.47,− 6.09] s, mean before-after shunt: 24.07–16.41 s); $p < 0.05$ ↓Time score 18MWT − 8.1 (95% C.I. [− 10.62, − 5.73] s, mean before-after shunt: 33.85–25.76 s); $p < 0.05$	–	–
Giannini et al., 2023 [7]	Instrumented gait analysis	↓ Time score (TUG) Before-after shunt: 2.79 (1.57–4.25)–4.45 (1.81–6.8) delta; $p < 0.001$	–	–

24 h of CSFTT. All of these gait parameters improved significantly after 24 h CSFTT under dual-task conditions. However, the step width was dependent on the type of dual-task, with non- significant improvements during forward counting and semantic fluency. Schniepp et al. [18] reported, that gait speed significantly decreased 24 h after CSFTT only while performing verbal fluency tasks not serial 7 subtractions.

Dynamic equilibrium measurements after shunt surgery

The Timed Up-and-Go test has been found to be most commonly used to assess functional performance and dynamic balance of gait, and demonstrated a reduction in step count, number of steps in 180° rotation, and time score after shunt surgery [24, 31, 35, 37, 39–41]. Furthermore, the 10MWT was used to assess changes between baseline and post-operative VP shunt surgery with significantly reduced time score and step count at both comfortable and maximal walking speed [31, 37]. The 18 m walk test provides another option for assessment, with significant changes in time and total number of steps found after surgery [24, 7].

Nine studies included dynamic equilibrium measurements performed at 6 months [24, 35, 41], 3 months [37, 39, 40], 1 month [36], on average 121 days [7], and 2 weeks after shunt surgery [31]. Seven studies used a reliable and valid TUG test that may be useful for dynamic equilibrium measurements between baseline and post-operative VP shunt surgery, where a reduction in TUG total time occurred [24, 31, 35, 37, 39–41]. Other statistically improved parameters of the TUG test included the number of steps and the number of steps in 180° rotation [24, 40]. In a retrospective study of 19 patients with iNPH, who underwent neurosurgery for VP shunt with low or medium valve pressure one month after a positive CSFTT, the results showed a mean improvement in TUG time [36].

Two studies used the 10MWT for baseline and post-operative VP shunt surgery assessments at 2 weeks [30] and 3 months [37]. Sundstrom et al. [37] confirmed a significant improvement in 10MWT in a large national cohort of patients ($n = 1400$), including stratification by sex and age. Matsuoka et al. [31] reported significantly reduced time score and number of steps at a comfortable walking speed. Significantly reduced time score and number of steps were also confirmed at maximal walking speed. Hulser et. al. [39] evaluated follow-up after a positive CSFTT response and 12 weeks after shunt surgery. Patients with iNPH had a significant decrease in time score and number of steps (at 10MWT.

Two studies found significant improvements in the 18 m walk test from baseline 121 days (on average) [7] and 6 months after shunt surgery [24]. During 18 mW patients were instructed to walk on a straight line at a self-selected pace along a large and empty corridor 30 m long. The test was repeated three times in order to filter out the effect due to habituation or lack of attention. Ferrari et al. [7] demostrated that the reduction of time score at 18 m walk test was − 8.1 s (95% C.I. [− 10.62, − 5.73] s, mean baseline: 33.85 s, after surgery: 25.76 s).

Quantitative analysis of the effects of shunt surgery on spatio-temporal, kinematic and kinetic parameters of gait

The most sensitive spatio-temporal parameters were self-selected walking speed followed by stride length, which increased significantly after shunt surgery [24, 33–36, 38]. Cadence demonstrated very inconsistent results after shunt surgery [24, 27, 32, 34, 35]. Single and double limb support between pre-CSFTT/post-CSFTT and post-shunt surgery provided rather controversial results in iNPH. Chen et al. [32] reported statistical significance in single and double limb support measured by the Vicon motion analysis system, with no dependence of post-shunt surgery changes on a positive CSFTT response. They found that none of the so-called balance-related gait parameters, including stride width and step height, changes after shunt surgery. In another study [34], the post-surgery evaluation showed increased range of motion of the hip, knee, and ankle joints in the sagittal plane during the gait cycle. However, based on kinetic analysis, the peak flexion moment of the hip during the stance phase was greater after shunt surgery. The improvement of the Evans index was significantly correlated with the improvement of walking speed, and with the total ranges of motion of the hip and ankle joints in the sagittal plane [34].

Nine studies investigated the spatiotemporal parameters of gait with different assessment times after shunt surgery [24, 27, 32–36, 38, 40]. They were evaluated at 6 months [24, 35], 3 months [32, 40], 1 month [27, 36], 1 week [33], an average of 19.5 days [34] and a range of 3 to 18 months [38]. Six studies [24, 27, 32, 33, 38, 40] compared spatiotemporal gait parameters between baseline and after shunt surgery, and only 3 studies [34–36] evaluated outcomes based on a positive CSFTT response.

In relation to spatiotemporal gait parameters, the most common findings were a significant trend for longitudinal increase of walking speed after shunt surgery [24, 33–36, 38]. Nikaido et al. [33] revealed increased walking speed (95% C.I. [− 0.24 to − 0.09] m/s, standardized mean difference: 0.58 m/s; $p = 0.004$) between baseline and post shunt surgery. Three studies [34–36] demonstrated that a significant decrease in walking speed occurs both after a positive CSFTT response and after the insertion of a VP shunt. Only two studies [27, 32] using an optoelectronic motion analysis system (Vicon 370) and plantar pressure time analysis did not observe an increase in gait speed after shunt surgery.

All studies evaluating stride length changes found a statistically significant increase in stride length between pre/post CSFTT and post shunt surgery [24, 32, 34, 35, 38]. Giannini et al. [24] confirmed that in both the TUG test and the 18 m walk test, most parameters improved significantly, especially stride length 6 months after surgery. Gait analysis using the VICON MX 10-camera motion analysis system confirmed a significant increase in stride length based on CSFTT positivity and shunt surgery [34].

Two studies [27, 33] assessed the stride time at baseline and after shunt surgery using a triaxial accelerometer. The results are inconsistent, as only Nikaido et al. [33] found smaller step counts(SMD 0.51, 95% CI 3.77 to 12.34, $p = 0.010$), shorter stride times (SMD 0.66, 95% CI 0.01 to 0.05 s, $p = 0.008$), and improved variability of stride time (SMD 0.88, 95% CI 2.59% to 7.60%, $p < 0.001$) after shunt surgery.

Cadence demonstrated very inconsistent results [24, 27, 32, 34, 35]. Three studies confirmed no significant changes in cadence after shunt surgery [24, 27, 35]. Measurements performed with the ProtoKinetics Zeno Walkway did not shown significant changes in cadence between baseline and after shunt surgery [35]. Moreover, kinematic analyses revealed inconsistent results: Kitade et al. [34] found a significant increase in cadence (, while Chen et al. [32] found a significant decrease in cadence for both the left limb and the right limb.

Parameters of gait cycle provided rather controversial results in iNPH. Three studies [27, 32, 35] assessed single limb support's changes between pre-CSFTT/post-CSFTT and post-shunt surgery, with only Sun [27] presenting no significant changes using plantar pressure-based temporal analysis, which has not been shown to be a valid measurement for the analysis of spatiotemporal gait parameters. Chen et al. [32] reported statistical significant changes in single and double limb support measured by the Vicon motion analysis system with no dependence on a positive CSFTT response. However, this is the only study supporting significant results of double limb support after shunt surgery [27, 38].

Five studies investigated the kinematic parameters of gait with different assessment times after shunt surgery. Patients were evaluated after 6 months [35], ranging from 3–18 months [38], with a mean time of 121 days [7], 19.5 days [34], or 1 month [33] after surgery. Kinematic analyses showed changes of total motion in the sagittal plane of the lower limb joints in positive responders to CSFTT and after VP shunt surgery. Total motion improved significantly in the hip and ankle joint in the sagittal plane. Although the ankle joint before shunt surgery was consistently held in dorsiflexion during the gait cycle, after shunt surgery this was changed to plantar flexion during the flat foot phase and terminal stance phase [34]. Further results evaluated the kinematic parameters of the ankle before CSFTT and after shunt surgery. Ferrari et al. [7] described a significantly improved angle of foot inclination in the sagittal plane measured during the TUG test, corresponding to the maximum distance of the foot between the mid-swing phase and initial contact. However, they did not find any changes in the total movement of the ankle joint in the frontal plane (toe in/out angle) assessed by computerized walkway [7].

Only one study by Kitade et al. [34] compared knee joint kinetics between a positive response to CFSTT and an average of 19.5 days after VP shunt surgery. The joint moment and force in the sagittal plane were normalized to body weight. For each kinetic parameter, the average values obtained from five trials were assessed using VICON NEXUS software. In pre-swing phase, the peak hip flexion moment, peak generation power of hip, and ankle joint increased significantly after surgery. Similarly, the peak absorption power and peak force generation of the knee joint significantly increased in the pre-stance phase. The peak absorption power of the hip joint in the terminal phase of stance significantly increased No significant changes were reported for peak extension moment of the knee and the peak plantar flexion moment of the ankle in the stance phase.

Discussion

The aim of this systematic review of the literature was to appraise gait changes occurring 24 h after a CSFTT, and after a VP shunt surgery in iNPH patients. Given the importance of CSFTT in the prognosis of iNPH and the decision to perform shunt surgery, quantification of gait changes has become clinically important in the last decade. However, many studies investigating gait changes 24 h after a CSFTT and after VP shunt surgery have used clinical gait scores rather than quantitative gait analysis procedures, leading to limited interpretability and comparability of results.

The studies [18, 26, 27, 30] have included a 'time-granular' follow-up after CSFTT (e.g., 24–48–72 h) with different time windows. Only the 24 h post-CSFTT period was always assessed for gait analysis. Two studies [33, 41] evaluated gait analysis between 48 and 72 h after CSFTT, but they only assessed gait analysis between baseline and shunt surgery. The Measurements in 24 h after CSFTT are widely accepted and that outcomes assessed across different time windows are difficult to compare. Due to the limited number of studies, it is not possible to compare assessments at different time points from CSFTT-48 h [18, 30] and 72 h [18, 26, 30, 33, 41].

Another aspect of the variable outcomes of gait parameters after CSFTT may represent the fact that higher volumes of CSF drainage report better outcomes. A high-volume CSFTT was performed with an aim to remove 30–50 ml. However, it should be emphasized that most studies involving higher volume drainage defined shunt responders with symptomatic improvement, not with improvement in daily activities [48]. Most of the studies in our review are in the range of 30–50 ml, only the study by Sun et al. [27] (20–40 ml) evaluated gait parameters with no changes in speed, cadence, stride time, single and double support time.

Age should also be considered, to evaluate possible different response to shunt. Thavarajasingam et al., [49] referred that when patients were divided into 3 age groups; the response rate was 62% for those aged < 70 years, 52% for those aged 70–80 years and 39% for those older than 80 years. The mean age of iNPH patients in our review ranged from 70–80 years, but there was no variability in outcome parameters after shunt surgery based on age [50, 51].

Comparison of clinical characteristics of iNPH with various neurological conditions, such as vascular dementia or Alzheimer's disease with concomitant urinary disorder presented similar global cognitive functioning and walking speed. The most quantitative reports focusing on gait analysis comparing iNPH patients with normal older adults or to patients with an identified alternate neurological or vascular condition, such as parkinsonism (iNPH-P +) or important vascular encephalopathy (v-iNPH) does not reflect daily practice and prevents better identification of cognitive and gait phenotypes [51, 53]. Defying expectations, severe vascular encephalopathy in patients with v-iNPH was not identified as a factor influencing a different post-CSFTT evolution [26].

Overall, respect to INPH-P −, INPH-P + patients showed worse performances in the majority of variables at baseline, post CSFTT and 6 months after VP shunt surgery. However, despite this group did not show a significant response after CSFTT, a significant improvement was observed 6 months after VP shunt surgery. This finding could have positive implications for clinical practice, as an unsatisfactory response to CSFTT in iNPH with parkinsonism should not be used as an exclusion criteria from VP shunt surgery [41]. Geneva protocol allowed to describe differences between iNPH and iNPH mimics when comparing gait before and after CSFTT during the dual–task condition: baseline gait performances were similar between iNPH and iNPH mimics, while iNPH patients improved significantly more their gait parameters (walking speed, stride length, step width and stance duration) after 24 h CSFTT during dual-tasking in comparison to iNPH mimics, the gait improvement during single task after CSFTT test were similar between iNPH patients and iNPH mimics [20].

Since improvement is seen predominantly in gait function, the TUG test and 10 m walking test (10MWT) are generally used to assess preoperative levels of cardinal symptoms and postoperative outcomes in iNPH. A significant decrease in time score at TUG test and 10MWT was demonstrated 24 h after a CSFTT and after shunt surgery [19, 20, 24, 25, 30, 31, 35, 37, 39–41]. Despite the potential benefit of the TUG test, it is not as commonly used as the 10MWT to measure walking speed in patients with iNPH [19, 20, 36, 39]. The 18 m walk test provides another option for assessment, with significant changes in time and total number of steps found after surgery [24, 7]. We found a moderate prognostic value of TUG test and 18 m walking test (18MWT) gait speed in predicting shunt outcomes among iNPH patients. Still, these tests suffer from limited specificity. A more accurate diagnosis can be achieved by examining gait parameters assessed at comfortable walking speed during the 10MWT [31].

The most frequently investigated spatio-temporal parameter evaluating the effect of the CSFTT and shunt surgery were walking speed and stride length, which both increased in most cases. Gait speed and stride length are absolutely important and valid spatiotemporal gait parameters evaluating the effect 24 h after a CSFTT and after VP shunt surgery [17, 22–24, 26, 28, 30, 38]. Moreover, these spatio-temporal gait parameters are a key feature of mobility impairments and have been linked to quality of life, mobility, and impaired everyday independence of patients with iNPH [23]. We suggested that an improvement in walking speed and stride length 24 h after CSFTT could be considered a relevant improvement [17]. Accordingly, clinicians should measure the effects on walking parameter 24 h after CSFTT at the time of maximum change to adequately estimate the capacity for improvement after therapy [18]. Loss of consistency in the ability to establish a steady gait rhythm, which leads to greater stride time and stride-to-stride variability, has been associated with balance disturbances leading to falls. However, stride time and stride length variability contribute to the controversy in the assessment of CSFTT effects and shunt surgery [20, 23, 27, 28, 33]. Cadence (number of steps) divided by walking time, is considered an important parameter in the evaluation of INPH. Regarding gait/balance, reduced cadence should be present in patients with iNPH. However, cadence demonstrated very inconsistent results between pre/post CFTT and post shunt surgery [24, 27, 32, 34, 35]. The results of several studies are poorly consistent regarding cadence, which was found to be unchanged or higher after a CSFTT and shunt surgery [22]. Ferrari et al. [26] reported that manifestations of shuffling gait are associated with reduced stride length and increased cadence. However, our results suggest that cadence is not able to detect differences with a healthy control group, and it is hence not suitable to consider in the evaluation of CSFTT and shunt surgery effects [24, 27, 35]. Parameters of gait cycle provided rather controversial results in iNPH as well. We assessed inconsistent changes in single limb support and double limb support between the pre-CSFTT/post-CSFTT and post-shunt surgery [17, 23, 26, 27, 32, 35].

Changes in balance-related gait parameters (stride width, step height, joint angle excursions) after CSFFT and shunt surgery are still a controversial area of research due to small sample sizes and low standardization [35]. Despite significant differences between iNPH and healthy controls in the percentage of swing, single and double support phases or step height and step width, there is still a lack of relevant evidence for the effect of the CSFTT and shunt surgery on these parameters [23, 27]. Idiopathic NPH is one of the frontal higher-level gait disorders including disequilibrium. Several studies have reported that patients with iNPH exhibit abnormalities in postural control with greater sway affecting speed, stride length, and stride width. It can be hypothesized that dynamic balance with voluntary postural control affects spatio-temporal gait parameters in iNPH more than static balance [8, 9, 33, 45, 46]. In particular, patients with high fall risk may consciously maintain lateral dynamic stability during gait to a greater extent than those with low fall risk. These results highlight the conscious component of motor control in pathological gait in iNPH. They provide clues for strategies to assess the effect of conscious gait between pre/post CFTT and post shunt surgery [40, 47].

Based on the Geneva protocol [20], balance-related gait parameters can be evaluated under dual-task conditions 24 h after CSFTT in iNPH. Improvement in stride width during the dual-task condition appears to be the most discriminating parameter. Interestingly, the discriminative properties of the gait parameters between iNPH and iNPH mimics were only observed in the dual-task conditions. These results suggest that combining quantitative gait assessment using dual-task paradigms after CSFTT could improve the clinical evaluation of frontal higher-level gait disorders in patients with a suspicion of iNPH and prior to shunting. Simultaneous assessment of gait and cognition using dual-task may better reflect the potential benefits of CSF tapping than a separate evaluation in iNPH patients [18, 20]. Other studies [52–55] also confirmed the benefit of simultaneous assessment of gait and cognitive functions in patients with iNPH at a time window other than 24 h after CSFTT. Promoting the standardization of dual-task evaluation could encourage other clinicians to use the new method to identify iNPH.

The joint angle excursions are other obvious equilibrium-related gait changes in iNPH [10, 11]. After CSFTT, a few studies have reported no detailed positive change angle excursions of hip, knee and ankle in the sagittal plane. Ankle joint motion in the frontal plane (toe-in/toe-out angle) did not confirm any significant change [17, 20, 22, 23, 28]. The joint angle excursions in the sagittal and frontal planes are not critical for the evaluation of positive effects after CSFTT. Studies evaluating joint angle excursions after shunt surgery are very heterogeneous due to the different time of outcome assessment after shunt surgery. Moreover, not all studies have considered the outcomes of prior CSFTT. The total sagittal plane motions of the hip, knee, and ankle joints during a gait cycle increased after shunt surgery. Especially, hip extension increased in the terminal stance phase and ankle plantar flexion angles in the pre-swing phase [34]. An improvement angle of foot inclination in the sagittal plane, corresponding to the maximum distance of the foot between the mid-swing phase and initial contact, has been described [7]. In addition, the propulsive force of the hip (generative force), knee (absorptive force), and ankle (generative force) in the pre-swing phase was restored after shunt surgery. Hip extension in the terminal stance phase and plantar flexion of the ankle in the pre-swing phase constitute the essential component of the propulsive force of forward motion. Results in the literature regarding joint motion, moment, and force provide further evidence of increased gait speed and stride length after shunt surgery [17, 7, 22, 34, 35].

Limitations

Studies were highly heterogeneous due to the lack of standard CSFTT and shunt surgery methodology. Various amount of CSF volume was removed during the tap test (20–50 ml) and also time to outcome assessment after CSFTT or shunt surgery differed in studies. Since there is no widely accepted time to outcome assessment, we decided to choose the most common 24 h window which seems to be long enough to detect functional changes and delay shunt surgery less significantly. From this point of view, the 24 h window is the earliest that can be used. Although there are studies indicating that the maximal increase in gait velocity can be observed in 24–48 h after CSFTT [18], and others report some improvement even one week later [55]. Patients undergoing CSFTT are not always diagnosed with definite iNPH and may fall under the category of possible iNPH. Some studies included patients with probable iNPH [24, 35, 41] and some with definite iNPH but lacked information on diagnostic criteria [27, 7, 31, 32, 36, 40].

Conclusion

Given the importance of CSFTT in the prognosis of iNPH and the decision to perform shunt surgery, quantification of gait changes has become clinically important in the last decade. The Timed Up and Go test and 10 m walking test are generally used to assess preoperative and postoperative levels of cardinal symptoms in iNPH. The most sensitive spatio-temporal parameters evaluated 24 h after CSFTT and shunt surgery was self-selected walking speed followed by stride length. Changes in balance-related gait parameters are still a controversial area of research. Combination of quantitative gait assessment using a dual-task paradigm after CSFTT could improve the clinical evaluation of higher-level frontal gait disturbances in patients with suspected iNPH before shunting.

Abbreviations

CSF	Cerebrospinal fluid
CSFTT	Cerebrospinal fluid tap test
iNPH	Idiopathic normal pressure hydrocephalus
PRISMA	Preferred reporting items form systematic reviews and meta-analyses
ROM	Range of motion
TUG	Timed up-and-go
VP	Ventriculoperitoneal

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author, [TD], upon reasonable request.

Declarations

Ethics approval and consent to participate

The study was carried out in accordance with the Helsinki Declaration of 1964 (2013 revision).

Competing interests

The authors declare no competing interests.

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