Postural control before and after cerebrospinal fluid shunt surgery in idiopathic normal pressure hydrocephalus

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Abstract

Objectives: This study aimed to confirm whether cerebrospinal fluid (CSF) shunting for idiopathic normal-pressure hydrocephalus (iNPH) improves postural instability, and to investigate the relationship between postural control and gait ability.

Patients and methods: Twenty-three iNPH patients and 18 age-matched healthy controls (HC) were examined using the timed up and go (TUG) test and a force platform for calculating the center of pressure (COP) trajectory during voluntary multidirectional leaning and quiescent standing. We determined the patients' TUG values and COP trajectories before and after shunt surgery.

Results: Postural sway was greater in iNPH patients before shunt surgery and the TUG value was lower in iNPH patients before shunt surgery than in HC. Voluntary COP movements were significantly improved in iNPH patients at 1 week post-surgery, but no significant changes in quiescent standing were found between pre- and post-surgery. Significant correlations were found between the TUG value and voluntary COP movements in iNPH patients before and after surgery, but no significant correlations were observed between the TUG value and quiescent standing.

Conclusion: Our results indicate that CSF shunting in iNPH patients may improve voluntary postural control and reduce the risk of falling. Impaired voluntary COP control in iNPH patients may reflect the underlying pathophysiological mechanisms of balance disturbance in iNPH.

Keywords

Idiopathic normal pressure hydrocephalus; Postural control; Balance disturbance; Force platform; Center of pressure; Cerebrospinal fluid shunting

1. Introduction

Idiopathic normal pressure hydrocephalus (iNPH) is characterized by progressive clinical symptoms including gait and balance disturbances, cognitive impairment, and urinary incontinence with brain ventricular dilation and normal cerebrospinal fluid (CSF) pressure [1]. Gait and balance disturbances in iNPH are important signs because these disturbances are likely to increase the risk of falling [2–6].

In Nutt's classification, iNPH is one of the frontal higher-level gait disorders represented by disequilibrium [7]. Equilibrium function can be assessed by standing postural sway using force platforms. Several studies have demonstrated that iNPH patients exhibit abnormalities in postural control with greater sway [5,8–10]. In addition, iNPH-associated balance disturbances with disequilibrium occur due to central and/or peripheral vestibular dysfunction [11–13]. However, the effect of CSF shunting on balance disturbance in iNPH remains controversial due to differences in the assessment of balance disturbance among previous studies [8,10–15].

Considering that CSF shunting for iNPH results in improvements in gait ability such as velocity, step length [14,16,17], and step width [18], it can be surmised that dynamic balance with voluntary postural control is more important than static balance. Our previous study reported that the center of pressure (COP) movement with voluntary leaning posture was poorer in iNPH patients than in Parkinson's disease (PD) patients and healthy elderly persons, but no difference in static postural control was found between these diseases [5]. In addition, it has been suggested that the impaired voluntary COP control in iNPH patients might represent the pathophysiological mechanisms underlying iNPH-associated postural instability [5]. Therefore, we hypothesized that the impaired voluntary postural control in iNPH patients would be improved by CSF shunting. This study aimed to evaluate the postural control changes before and after CSF shunting in iNPH patients and to investigate the relationship between postural control and gait function.

2. Patients and methods

2.1. Participants

iNPH patients and healthy control subjects (HC) were recruited from the Department of Neurosurgery and Rehabilitation Medicine at the Osaka Medical College Hospital. Patients were excluded for (1) additional neurological or orthopedic disorders, (2) inability to walk unassisted for 10 m, and (3) postoperative pain or fatigue affecting gait and balance. Under these criteria, three patients were excluded from this study. In total, 23 iNPH patients and 18 HC participated in this study. The HC did not exhibit any neurological or orthopedic abnormalities. Table 1 presents the demographic data of the participants. The study protocol was approved by the ethics committee at Osaka Medical College, and all participants provided informed consent.

The patients received probable diagnoses of iNPH with positive results in the CSF tap test according to the iNPH diagnostic criteria [19]. They underwent ventriculoperitoneal (VP) or lumboperitoneal (LP) shunt surgeries at Osaka Medical College Hospital approximately 1 month after the CSF tap test. Our first choice of surgical treatment was LP shunt surgery, while VP shunt surgery was selected when lumbar spinal deformity and spinal canal stenosis were observed. A Codman-Hakim programmable valve with a Siphon-Guard (Codman and Shurtleff, Raynham, MA) was implanted in all patients and initial pressure settings were determined according to the patients' height and weight in reference to Miyake's quick reference table [20]. Each patient's cognitive function was assessed using the Mini-Mental State Examination (MMSE) before the shunt surgery, and the history of falling within the 6 months prior to surgery was recorded.

2.2. Postural control and gait assessment

The patients were examined 1 day before and 1 week after CSF shunt surgery.

2.2.1. Postural control examination using a force platform

Postural control examinations were conducted using a force measurement apparatus consisting of a platform (20 mm height × 690 mm width × 400 mm length) and sensor area (470 mm × 320 mm) with Foot Print software (Zebris Medical GmbH, Isny, Germany). This platform can record the vertical pressure on each 0.5 cm^2 area of its surface at a sampling rate of 60 Hz.

Postural control examinations consisted of quiescent standing and voluntary multidirectional leaning tests, as described previously [5]. Fig.1 illustrates the measurement setup of the force platform examinations. The standing foot position of the subjects was fixed at a 10 cm heel-to-heel distance.

With regard to the quiescent standing test, the participants were instructed to stand with a natural posture with open eyes, and the COP trajectory was recorded for 30 s [5].

With regard to the voluntary multidirectional leaning test, participants were instructed to lean in four different directions (as far forward, backward, right, or left as possible for 10 s in each direction) without bending their trunk or hip joints or lifting their feet from the force platform [5]. Moreover, when the subjects reached the maximum leaning posture, they were instructed to remain still without body sway. The examiner carefully observed whether the feet in the leaning test were in contact with the force platform. Additionally, the examiner sat behind the participants to prevent falls. The COP trajectory at maximum leaning in each direction was recorded for 10 s [5]. The postural control examinations were conducted in triplicate. To prevent fatigue, the participants were allowed to sit on a chair for 1 min between trials in the postural control examinations.

2.2.2. COP analysis for the postural control examinations

The postural sway parameters were calculated as the locus length and sway area from the recorded COP trajectory [5,10,21]. COP analysis of the voluntary multidirectional leaning test was defined as described previously [5]. The mean anterior-posterior axis displacement (COP_y) and the medial-lateral axis displacement (COP_x) were calculated from the COP trajectory during maximal leaning posture in each direction. Forward-backward and right-left distances were calculated from the COP_y and the COP_x [5] (Fig. 1). The stability area was defined as the rectangular region over which a subject could safely perform voluntary COP movements (i.e., forward-backward and right-left distances) without changing the foot position [5] (Fig. 1). The mean values from three trials were used for the COP analysis.

2.2.3. Gait function using the timed up and go test

The timed up and go (TUG) test is a validated test of functional mobility to assess gait-balance function [22], and recorded values have been demonstrated to correlate well with the incidence of falls [23]. The participants performed three normal-paced TUG trials, and the mean time of the three trials was used for analysis.

2.3. Statistical analysis

Statistical analyses were performed using JMP Pro v. 13.0 (SAS Institute, Cary, NC). The Shapiro-Wilk test was applied to determine the normality of the datasets.

According to the results, an unpaired-t test or the Mann-Whitney U test were conducted to test for significant differences in the postural sway parameter variables and TUG values between the iNPH patients at pre-surgery and the HC. Additionally, a paired-t test or the Wilcoxon signed-rank test were conducted to test for significant differences in the postural sway parameter variables between pre- and post-surgery in iNPH patients. To confirm the relationship between gait and postural control function, a Pearson's correlation was performed on the TUG values and postural sway parameter variables at pre- and post-surgery in the iNPH patients. Statistical significance was defined as $p < 0.05$. The data are presented as mean ± standard deviation.

3. Results

3.1. Participants' cognitive function and history of falling

The patients' cognitive function was within the normal range as determined by the MMSE scores (25.6 ± 3.1). Nineteen patients (82.6%) had a history of falling in the 6 months prior to surgery.

3.2. COP analysis for quiescent standing

The locus lengths and sway areas in the iNPH patients at pre-surgery were significantly greater than those in the HC (locus length: $p < 0.001$, sway area: $p < 0.001$) (Table 2). In the patients with iNPH, there were no significant differences in the postural sway parameters during quiescent standing between pre- and post-surgery (locus length: $p = 0.164$, sway area: $p = 0.113$,) (Table 2).

3.3. COP analysis for the voluntary multidirectional leaning test

Compared to the HC, the iNPH patients exhibited significantly longer locus lengths in all directions (forward: $p < 0.001$, backward: $p < 0.001$, right: $p < 0.001$, left: $p < 0.001$), significantly greater sway areas in all directions (forward: $p < 0.001$, backward: $p < 0.001$, right: $p < 0.001$, left: $p < 0.001$), significantly shorter leaning distances in both the forward-backward ($p < 0.001$) and right-left ($p < 0.001$) directions, and significantly smaller stability areas ($p < 0.001$) at the pre-surgery examination (Table 2).

In patients with iNPH, no significant differences were found between pre- and post-surgery in postural sway in forward and backward leaning directions (forward; locus length: $p = 0.894$, sway area: $p = 0.449$, backward; locus length: $p = 0.224$, sway area: $p = 0.182$) (Table 2). The sway areas during right and left leaning were significantly smaller post-surgery than pre-surgery (right: $p = 0.007$, left: $p = 0.037$), and there were no significant differences in the locus lengths during right and left leaning between pre- and post-surgery (right: $p = 0.693$, left: $p = 0.503$) (Table 2). With regard to voluntary COP movement, the forward-backward and right-left distances were significantly longer post-surgery than pre-surgery (forward-backward distance: $p = 0.002$, right-left distance: $p < 0.001$), and the stability area was significantly greater post-surgery than pre-surgery ($p < 0.001$) (Table 2).

3.4. TUG test

The mean TUG value of the iNPH patients at the pre-surgery examination was significantly slower than that of HC ($p < 0.001$), whereas the mean TUG value of iNPH patients at the post-surgery examination was significantly faster than that at the pre-surgery examination ($p < 0.001$) (Table 2).

3.4. Correlation between the TUG value and the COP parameter variables

In the patients with iNPH, significant correlations were found between the TUG values and voluntary COP movement at the pre-surgery examination with regard to forward-backward distance ($r = -0.434$, $p = 0.002$), right-left distance ($r = -0.579$, $p = 0.004$), and stability area ($r = -0.454$, $p = 0.029$) (Table 3). After shunt surgery, significant correlations were found between the TUG values and voluntary COP movement with regard to forward-backward distance (r = -0.459, p = 0.028), right-left distance (r = -0.634, p = 0.001), stability area (r = -0.517, p = 0.012), and sway area during backward leaning (r = -0.434, p = 0.012) (Table 3). There were no significant correlations between the TUG values and other postural sway parameters at both pre- and post-surgery (Table 3). In the HC, no significant correlations were found between the TUG values and any postural sway parameters (Table 3).

4. Discussion

We aimed to explore whether CSF shunting for iNPH patients can improve postural control, and whether a relationship between postural control and gait functions exists.

Based on the underlying pathophysiology, iNPH patients manifest a frontal higher-level gait disorder with disequilibrium [4,7]. To date, the effect of CSF drainage on balance disturbance with disequilibrium in iNPH remains controversial because previous studies have used different methodologies such as a force platform [8,10], dynamic posturography [11,12], subjective body vertical evaluation [13], shoulder tug test [14], or gyroscopic systems [15]. However, these postural assessments cannot evaluate aspects of postural control with voluntary weight shifting. Considering that CSF shunting for iNPH elicits gait improvements such as gait velocity, step length [14,16,17], and step width [18], we surmised that postural control with voluntary movement may be more important than static movement when testing balance disturbance in iNPH patients.

In this study, our results indicated that CSF shunting in iNPH patients improved postural control with voluntary COP movements rather than static postural control. Furthermore, there were correlations between the balance-gait function with regard to the TUG value and voluntary COP movements in terms of forward-backward distance, right-left distance, and stability area during voluntary multidirectional leaning both before and after surgery, whereas no significant correlation was observed between the TUG value and postural sway during quiescent standing before or after surgery. iNPH-associated postural instability is thought to occur as a result of disequilibrium with central and/or peripheral vestibular dysfunction [11–13]. The voluntary multidirectional leaning test should be used to assess equilibrium functions rather than the postural function test during quiescent standing because the voluntary leaning posture requires maintenance of stable posture with voluntary COP movement such as internal perturbation [5]. Therefore, impairment of voluntary postural control can be detected using the multidirectional leaning test and its improvements may reflect the pathophysiological mechanisms associated with the disequilibrium-induced balance disturbance in iNPH. In contrast, the results of the HC in this study indicated no significant correlation between the TUG value and the postural sway parameters. The TUG value was likely influenced by ceiling effects because balance disturbances were not observed in the HC [24,25].

We found no significant difference in the postural sway parameters during quiescent standing between pre- and post-surgery. Similarly, a previous study reported that the stance condition with the feet forming an open angle indicated poor improvement of postural sway compared to the stance condition with the feet forming a closed angle during quiescent standing after CSF shunting [8]. In the present study, the stance width during quiescent standing was fixed at a 10 cm heel-to-heel distance. This quiescent standing position may compensate for the postural instability in iNPH. Therefore, we could not detect any significant changes in postural sway before and after shunt surgery during quiescent standing. In contrast, Czerwosz et al. reported that the postural sway during quiescent standing in iNPH was improved after CSF shunting, although the stance width in the postural examination was the width at which the subject was comfortable [10]; hence, it is difficult to compare these results to those of the present study. Another possible explanation for the non-effect of shunt surgery on postural stability during quiescent standing may be that the symptomatic improvement is still in progress for approximately 1 week after surgery. However, despite such non-optimal conditions, the voluntary COP movement during the leaning task was indicative of improvement 1 week after surgery. We believe that these findings may be fundamental in the study of iNPH-associated balance disturbance, and may also be meaningful in clinical practice such as in the evaluation of treatment effects and in tips for exercise therapy in rehabilitation interventions.

Our previous study demonstrated that postural control during voluntary lateral leaning was poorer in iNPH patients than in PD patients [5]. In the present study, we found that postural sway during voluntary lateral leaning was significantly improved in iNPH patients after surgery. Furthermore, right-left COP distances in voluntary lateral leaning were highly correlated with the TUG value both before and after surgery. These findings may reflect the pathophysiological mechanisms of postural and gait instability in iNPH. In addition, lateral postural control may be a key factor in the balance disturbance in iNPH because previous studies have reported that a wide-based gait can compensate for the deterioration of dynamic equilibrium [16,17].

In this study, although the stability areas represented by voluntary COP movement were markedly smaller in iNPH patients after surgery than in HC, the stability area was found to be significantly expanded in iNPH patients after surgery. Furthermore, it was found that there was a significant correlation between the stability area and the TUG value both before and after shunt surgery. Narrowing of the stability area has been demonstrated to be associated with restricted freedom of motion and a higher risk of falls [5,26–28]. The TUG value has also been demonstrated to correlate well with the incidence of falls [23]. Indeed, 82.6% of our patients had a history of falls in the 6 months prior to the study. Therefore, we believe that the improvement in voluntary COP movement after shunt surgery in the iNPH patients may contribute to the reduction in the risk of falls.

Gait disturbances are the most common symptom of iNPH, affecting 94-100% of patients with iNPH [29–31]. In this study, we found a correlation between gait function and voluntary COP movements both pre- and post-shunt surgery. In order to ensure a stable gait, it is necessary to control postural balance during voluntary movement. Our findings suggest that rehabilitation interventions focusing on voluntary COP control can improve gait ability in iNPH patients.

This study has several limitations. First, it should be noted that interpretation of the results of this study cannot necessarily be generalized because the foot position in the postural examinations using a force platform was fixed at a 10 cm heel-to-heel distance. Second, the number of participants in this study was relatively small and the participants were recruited from a single facility. Consequently, none of those testing procedures have showed a sensitivity and specificity high enough for the translation into a routine clinical procedure. Third, because the current results are short-term postoperative (i.e., non-optimal conditions), the long-term changes in postural functions remains unclear. Future studies should include a long-term follow-up of the changes in postural functions and examine whether additional physiotherapy interventions for iNPH patients after shunt surgery are effective or not.

In conclusion, our results suggest that the impairment of voluntary postural control in iNPH patients may be characterized by pathophysiological mechanisms of balance disturbance. CSF shunting for iNPH patients may improve postural control during voluntary movement and contribute to a reduced risk of falling.

Conflict of interest statement

The authors have no conflicts of interest to declare.

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Figure Captions

Fig. 1. Depiction of the voluntary multidirectional leaning test and quiescent standing. The thick arrows indicate the leaning direction. The locus lines indicate COP trajectory. The dashed lines indicate the stability area.

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Table 1
Participant characterisitics.

	iNPH (n = 23)	HC (n = 18)	*p* -Value
Age (years)	76.9 (4.7)	75.6 (4.1)	0.146[a]
Gender (male/female)	16/7	11/7	0.571[b]
Hight (cm)	158.9 (9.0)	161.1 (7.6)	0.648[a]
Weight (kg)	59.5 (11.5)	58.1 (7.4)	0.489[a]
MMSE score (pre-surgery)	25.6 (3.1)	—	
History of falls (%)	82.6	0	0.000[b]
Surgery type (LP/VP)	18/5	—	

Values are mean (SD); [a] *p* -value of paired-t test; [b] *p* -value of Chi-Square test;
MMSE: Mini Mental State Examination
LP: lumbo-peritoneal shunt; VP: ventriculo-peritoneal shunt

Table 2
Results of COP analysis for postural control examinations and TUG in iNPH and HC.

	iNPH pre-surgery (n = 23)	iNPH post-surgery (n = 23)	HC (n = 18)	*p*-Value iNPH pre vs. post	*p*-Value iNPH pre vs. HC
Quiescent standing					
locus length (mm)	663.6 (178.5)	631.1 (136.4)	225.0 (52.3)	0.164[a]	**<0.001[c]**
sway area (mm^2)	234.2 (115.5)	201.6 (84.4)	65.4 (17.1)	0.113[a]	**<0.001[d]**
Voluntary forward leaning					
locus length (mm)	300.5 (78.1)	302.5 (76.1)	152.9 (33.4)	0.894[a]	**<0.001[d]**
sway area (mm^2)	165.4 (72.6)	150.8 (70.0)	81.6 (23.9)	0.449[a]	**<0.001[d]**
Voluntary backward leaning					
locus length (mm)	311.1 (75.9)	340.9 (84.1)	166.5 (34.6)	0.224[b]	**<0.001[c]**
sway area (mm^2)	184.2 (69.5)	162.2 (71.0)	86.0 (19.7)	0.182[a]	**<0.001[d]**
Voluntary right leaning					
locus length (mm)	288.7 (70.3)	293.6 (63.4)	148.2 (30.3)	0.693[b]	**<0.001[c]**
sway area (mm^2)	217.9 (111.4)	169.2 (86.1)	87.7 (29.9)	**0.007[b]**	**<0.001[c]**
Voluntary left leaning					
locus length (mm)	290.8(65.3)	300.7(68.6)	151.9 (29.1)	0.503[b]	**<0.001[d]**
sway area (mm^2)	206.8 (85.6)	176.1 (67.6)	91.8 (22.4)	**0.037[a]**	**<0.001[d]**
Forward-backward distance (mm)	33.2 (25.3)	44.6 (25.8)	86.0 (18.5)	**0.001[b]**	**<0.001[c]**
Right-left distance (mm)	83.4 (35.9)	102.9(42.3)	147.9 (18.3)	**0.002[b]**	**<0.001[c]**
Stability area (cm^2)	34.5 (39.9)	54.6 (49.9)	128.9 (37.8)	**<0.001[b]**	**<0.001[c]**
TUG (sec)	18.8 (6.6)	15.1 (5.1)	7.8 (0.7)	**<0.001[b]**	**<0.001[c]**

Values are mean (SD); [a] p-value of paired-t test; [b] p-value of Wilcoxon signed-rank test; [c] p-value of Mann-Whitney's U test; [d] *p*-value of unpaired-t test.

Table 3

Correlation between TUG and COP parameter variabiles in iNPH and HC.

COP parameter variabiles	iNPH pre-surgery (n =23)		iNPH post-surgery (n=23)		HC (n =18)	
	r	*p* -Value	*r*	*p* -Value	*r*	*p* -Value
Quiescent standing						
locus length	0.269	0.215	0.207	0.343	0.147	0.567
sway area	0.039	0.859	-0.175	0.426	0.014	0.996
Voluntary forward leaning						
locus length	0.141	0.521	-0.035	0.873	0.067	0.791
sway area	-0.053	0.810	-0.054	0.807	0.346	0.159
Voluntary backward leaning						
locus length	-0.131	0.551	-0.301	0.163	0.200	0.427
sway area	-0.207	0.344	**-0.434**	**0.039**	0.252	0.313
Voluntary right leaning						
locus length	-0.093	0.674	-0.051	0.818	0.254	0.310
sway area	-0.282	0.193	-0.135	0.538	0.285	0.251
Voluntary left leaning						
locus length	0.064	0.773	-0.033	0.881	0.139	0.581
sway area	-0.265	0.223	-0.388	0.068	0.119	0.639
Forward-backward distance	**-0.434**	**0.039**	**-0.459**	**0.028**	-0.325	0.188
Right-left distance	**-0.579**	**0.004**	**-0.634**	**0.001**	-0.237	0.345
Stability area	**-0.454**	**0.029**	**-0.517**	**0.012**	-0.340	0.168

r: Correlation coefficients of Pearson's correlation.