Journal of the Neurological Sciences 398 (2019) 45–49

Contents lists available at ScienceDirect

Journal of the Neurological Sciences

journal homepage: www.elsevier.com/locate/jns

Gait analysis in a component timed-up-and-go test using a smartphone application

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ARTICLE INFO

Keywords:
Smartphone
Gait
Hydrocephalus
Aged

ABSTRACT

Background: The timed-up-and-go test (TUG) is a popular test for mobility, but it only measures the total time to complete tasks. Recent advances in smartphone technology enables measuring respective times of 6 components in the test (Stand, Go, Turn1, Come, Turns and Sit). We examined availability of these data for assessing different gait patterns.

Methods: This study enrolled 32 patients with probable idiopathic normal-pressure hydrocephalus and 87 age-matched active participants as controls. All the patients responded positively to cerebrospinal fluid (CSF) removal, among whom 19 underwent surgery with positive outcomes. The TUG was performed using a free smartphone application. The components were automatically detected, and their respective times were computed. Statistical analyses included item cluster analysis.

Results: In the control group, high correlations ($r \geq 0.7$) were observed in two pairs of Go and Come, and Turn1 and Turn2, which reflect straight walk and turn. This pattern was lost in the baseline and after CSF removal in the hydrocephalus group. After surgery, the two pairs in the control group regained high correlations. The item cluster analysis showed the pattern changes more clearly.

Conclusions: A smartphone is useful for analyzing gait patterns in the TUG, which can be applicable for various gait disorders.

1. Introduction

The timed-up-and-go test (TUG) is a popular test to assess gait and balance, and requires a subject to stand from a chair, walk straight, turn at a marker, come back, turn again, and sit down [1]. It measures the total time of performing these tasks, which are all basic components of mobility and daily activities. It is used to assess gait ability in aged individuals [2,3] and various disorders including Parkinson's disease [4] and idiopathic normal pressure hydrocephalus (iNPH) [5]. With the recent development of advance smartphones/tablets equipped with inertial gyroscopes and accelerometers, dynamic changes during each component of the TUG can be measured. This has helped in obtaining more detailed and clinically relevant information about a patient with movement disorders [6,7]. In this study, we examined the usefulness of measuring the times of 6 components of the TUG using an iPhone and a free application (Senior Quality, Digital Standard Co.) in active aged participants and patients with iNPH and exploring changes in gait patterns.

2. Methods

2.1. Participants

The study design and protocol were approved by the ethics committee for human research of Rakuwakai Otowa Hospital (Raku-Oto-Rin-17-010). The participants were recruited from March 2017 to March 2018. The participants or their representatives provided written informed consent for study participation.

The participants were allocated into two groups. The first group included 87 active aged individuals who participated in a 3-h Activity-Keeping Program for the Aged, one or two times every week (control group), in Rakuwa Villa Ilios. The program included individual

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https://doi.org/10.1016/j.jns.2019.01.023
Received 10 October 2018; Received in revised form 14 December 2018; Accepted 14 January 2019
Available online 16 January 2019

exercises supervised by physiotherapists, group exercises, and brain training for the aged community in our nearby area. The individuals who participated in this program had several disorders including stroke, cardiac disorders, and hip joint fracture, but they were still willing to continue their daily activities. Medical information including stopping criteria for exercise was obtained from family doctors for all participants. A past history of falling causing hip joint fracture was included in the count of fall incidents.

The second group was composed of 32 patients with possible iNPH, who were admitted to Rakuwakai Otowa Hospital (NPH group). Possible iNPH was defined as at least one component of the NPH triad (gait disturbance, dementia, and urinary incontinence) with ventriculomegaly on computed tomography (CT)/magnetic resonance imaging (MRI). Probable iNPH was defined as at least one component of the NPH triad with tight high convexity on CT/MRI or improvement of symptoms after cerebrospinal fluid (CSF) tap test or drainage, in accordance with the Japanese guidelines for the management of iNPH [8]. The tap test was performed by removal of 30 ml of CSF through a spinal tap, and responses were examined on the next day after the tap. An instrumented TUG (iTUG) study was performed in 43 patients with possible iNPH. Among them, 34 patients showed improvement of symptoms. Two patients with a total timing of > 60 s on the iTUG were excluded from the study. Subsequently, 32 patients with probable iNPH were recruited in the study. The data of the NPH group included baseline status (NPHbase) and the changes after the tap test (NPHtap). Among the 32 patients, 19 underwent ventriculoperitoneal CSF shunt surgery. The surgery was performed at ≥ 1 month after the tap test, with symptomatic improvement in all the patients (NPHshunt), based on an improvement of ≥ 1 point in the iNPH grading scale [8]. The data of the NPHshunt group were obtained at 1 week after the surgery (7.2 ± 1.4 days).

2.2. Data acquisition

The iPhone was fixed on the abdomen with an elastic belt at the level of the navel over the participant's clothes. The elastic belt had an inside pocket, which allowed smartphones to hang over the pocket.

The participants performed the iTUG twice. The iTUG trials were sequential. The participants were instructed to perform this task as fast as possible without running. In this study, an armless chair was used to decrease personal differences in power in the upper arm. After receiving the go signal, the participants arose from the chair (Stand), walked straight to 3 m (Go), turned around from a mark (Turn1), walked back (Come), turned back again (Turn2), and finally sat down (Sit). Data collection was automatically stopped at 2 s after sitting on the chair, and these data were transmitted automatically to the cloud database. The total time was manually measured simultaneously in two sessions in the NPH group and only in the first session of the TUG in the control group.

In this study, the total and the respective times for 6 components of the TUG were analyzed. An algorithm was developed to detect the 6 components of the iTUG, using the data obtained with an inertial gyroscope. With reference to previous studies [6,7], the segmented time of standing from a chair (Stand) was calculated on the basis of the pitch of the angular velocity (degree/s) obtained with the inertial gyroscope (Fig.1). The other 5 segmented times were calculated on the yaw of the angular velocity obtained by using the inertial gyroscope, for example, 0° for Go, 180° for Come and 360° for Sit.

2.3. Data analysis

All statistical analyses were performed by using an open source software R (version 3.3.2; R Foundation for Statistical Computing, Vienna, Austria; http://www.R-project.org). Continuous data are presented as mean and standard deviation; categorical data, as prevalence rate and percentage. The means of the two groups were compared using

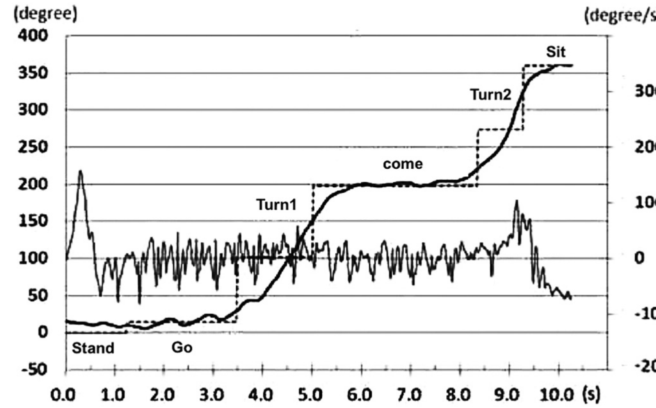

Fig. 1. Wavelet analysis of raw data in the instrumented timed-up-and-go test using the iPhone equipped with an inertial gyroscope. The segmented time of standing from a chair (Stand) was calculated based on the basis of the pitch of the angular velocity (degrees/s) obtained using the inertial gyroscope. The other 5 segmented times (Go, Turn1, Come, Turn2 and Sit) were calculated on the yaw of the angular velocity. In the presented case, 0°indicated Go ; 180, Come and 360°, Sit.

the Welch two-tailed *t*-test. Statistical significance was set at 0.05 (two-tailed). Interclass correlation coefficients were examined by using the "psych" packages (version 1.8.3) of the R [9]. Then, we examined the gait patterns of the 6 TUG components by computing correlation coefficients and performing an item cluster analysis [10,11]. In the NPH group, the underlying structures of the baseline data were also compared with those after the tap test and after the surgery. The item cluster analysis is a hierarchical cluster analysis of the items (variables), and not of the subjects [10]. It is characterized by the combined use of the Cronbach's coefficient alpha, the mean split-half correlation and Revelle's coefficient beta, the worst split-half correlation, which provides a clearer identification of the homogeneity and internal dimensional structure of clusters [10,11]. It also provides a goodness-of-fit index, ranging from 0 to 1, for each solution, which is useful when comparing the quality of different clustering solutions [11].

3. Results

Data of the clinical characteristics are summarized in Table 1. No statistically significant differences in age, sex, and severities based on modified Rankin scale between the two groups. The NPHbase group showed a statistically significantly higher frequency of falling history than the control group.

The total times of in the TUG were markedly longer in the NPH group than that in the control group, both in the manual TUG (mTUG) and iTUG. The interclass correlation between the mTUG and iTUG times was high in both groups (0.93 and 0.94, respectively).

The total times in the first session of the mTUG and iTUG in the control, NPHbase, NPHtap and NPHshunt groups were obtained for all the participants. The total times in the second session in iTUG were obtained in 81.2% - 100% of the participants. In the control group, the first and second iTUG times were 12.5 s (mean) and 10.9 s (mean), respectively. In the NPHbase group, they were 19.4 s and 18.1 s, respectively. Thus, the iTUG times in the second session were shorter in both groups. In the wavelet analysis, the data of the 6 components of the iTUG in the first session in four groups were obtained in 87.5% to 100% of the participants. The iTUG data in the second session in the NPH groups were obtained in 50.0% to 78.9% of the participants. Although a statistically significant difference was observed only in the NPHbase group, the success rates of the segmentation in the second session tended to be lower in the other NPH groups.

To examine the gait characteristics of the patients with iNPH, the following analyses were performed using the data from the first session

Table 1
Clinical characteristics of the Control group and NPH group.

	Control	NPHbase	p
Number	87	32	
Age	79.4 ± 7.0	77.6 ± 5.5	0.142
Male (%)	46.0	68.8	0.268
mRS			0.226
(G2)(%)	42.5	65.6	
(G3)(%)	50.6	21.9	
(G4)(%)	6.9	12.5	
Falling (%)	21.5	68.8	< 0.001*
Total time of mTUG1(sec) (success rate: %)	11.4 ± 4.1 (100)	18.5 ± 9.6 (100)	< 0.001*
Total time of iTUG1(sec) (success rate: %)	12.5 ± 4.1 (100)	19.4 ± 9.4 (100)	< 0.001*
interclass correlation coefficients (95%CI)	0.93 (0.76–0.97)	0.94 (0.89–0.97)	
Total time of iTUG2(sec) (success rate %)	10.9 ± 4.1 (87.4)	18.1 ± 7.8 (81.2) (NPHtap 87.5) (NPHshunt 100)	< 0.001*
Success rate of wavelet analysis (1st / 2nd) (%)	99.2 / 86.2	87.5 / 50 (NPHtap 90.5 / 58.3) (NPHshunt 100 / 78.9)	

Abbreviations. CI: confident interval, G: grade, iTUG1/2: instrumented timed-up and go test (1st/2nd session), mTUG: manually assessed timed-up and go test, NPH: idiopathic normal pressure hydrocephalus, NPHbase: baseline state in NPH, NPHshunt: after shunt surgery in NPH, NPHtap: after the tap test in NPH.

* Statistical significance was set at 0.05 (as written in Data analysis section).

of the iTUG:

Comparison of the 6 iTUG components among the 4 groups showed that statistically significant changes were noted in 4 components, namely Go, Come, Turn2, and Sit (Fig. 2). In the NPH group, improvement after surgery was observed in all 4 components. The Pearson correlation coefficients among the 6 components of the iTUG were examined (Table 2). In the control group, high correlations ($r \geq 0.70$) were observed in the pairs Go and Come, and Turn1 and Turn2. In the NPHbase group, high correlations were observed in the pairs Go and Turn1, Go and Come, Turn1 and Come, and Turn1 and Turn2. In the NPHtap group, high correlations were observed in the pairs Go and Turn1, Go and Turn2, and Turn1 and Come. In the NPHshunt group, high correlations were observed in the pairs Go and Turn1, Go and Come, and Turn1 and Come.

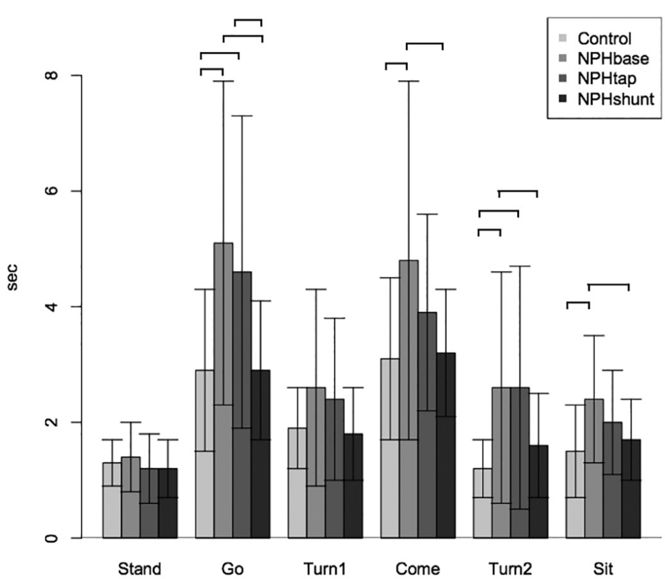

Fig. 2. Times (*sec*) of the six components of the instrumented timed-up-and-go test in the control, NPHbase, NPHtap, and NPHshunt groups. Statistically significant changes in all components except for Stand were observed. The square bracket indicates a pair with a statistical significance.

Table 2
Correlation coefficients between two pairs among 6 components of timed-up and go test in the Control, NPHbase, NPHtap, and NPHshunt groups.

	Control	NPHbase	NPHtap	NPHshunt
data obtained / total	86 / 87	28 / 32	29 / 32	19 / 19
Stand: Go	0.21	0.18	−0.41	0.27
Stand: Turn1	0.36	0.13	−0.13	0.28
Stand: Come	0.28	0.13	0.03	0.23
Stand: Turn2	0.29	0.28	−0.24	0.50
Stand: Sit	0.01	0.16	0.35	0.26
Go: Turn1	0.56	0.72	0.78	0.71
Go: Come	0.88	0.81	0.66	0.96
Go: Turn2	0.57	0.67	0.79	0.42
Go: Sit	0.18	−0.24	−0.31	0.16
Turn1: Come	0.55	0.92	0.84	0.75
Turn1: Turn2	0.76	0.82	0.56	0.66
Turn1: Sit	−0.10	−0.08	−0.25	−0.11
Come: Turn2	0.55	0.64	0.29	0.40
Come: Sit	0.21	−0.01	−0.05	0.09
Turn2: Sit	−0.14	−0.07	−0.23	0.19

Abbreviations. CI: confident interval, G: grade, iTUG1/2: instrumented timed-up and go test ($1^{st}/2^{nd}$ session), mTUG: manually assessed timed-up and go test, NPH: idiopathic normal pressure hydrocephalus, NPHbase: baseline state in NPH, NPHshunt: after shunt surgery in NPH, NPHtap: after the tap test in NPH.

In the item cluster analysis using data from the first session, we paid attention to Cluster1 and Cluster2. In the control group (Fig. 3A), the pair Go and Come became Cluster1, and the pair Turn1 and Turn2 became the Cluster2. In the NPHbase group (Fig. 3B), this pattern was lost and the pair Turn1 and Come became Cluster 1. After the tap test (Fig. 3C), the pair Turn1 and Come was Cluster1 and the pair Go and Turn2 became the Cluster2. After the shunt surgery (Fig. 3D), the pairs Go and Come, and Turn 1 and 2 were Cluster1 and Cluster2, respectively. Thus, the gait pattern was restored in patients with iNPH after the shunt surgery, as in the control group.

4. Discussion

The present study aimed to assess the gait disturbance in patients with iNPH using a smartphone application. The results showed a high correlation between the total mTUG and iTUG times. Furthermore, the smartphone application showed a capability to measure the time in each TUG component, which is useful for assessing gait patterns in iNPH.

Among the symptoms of iNPH, gait disturbance is the most common symptom [12]. Gait disturbance is characterized by slow, short-stepped, broad-based and shuffling gait with outward rotated feet [13]. It differs from the typical Parkinsonian gait in broad-based gait with outward rotated feet.

Gait analysis is usually performed using an electric walkway. It could measure many gait parameters such as gait speed, cadence, step length, stride length, double support time and their variabilities. It provided useful information about gait patterns in older adults [3], and in various disorders such as Parkinson's disease [14]. Using the electric walkway for patients with iNPH patients, Williams et al. reported that the degree of improvement after drainage significantly correlated to the degree of post-shunt improvement in velocity, double support time, cadence, and stride length [15]. However, this is somewhat costly and non-wearable. Currently, advance smartphones equipped with an inertial three-dimensional accelerometer and gyroscope are available and enable measurement of gait characteristics without large-scale machines. Their reliability has been confirmed [6], even for the effects of

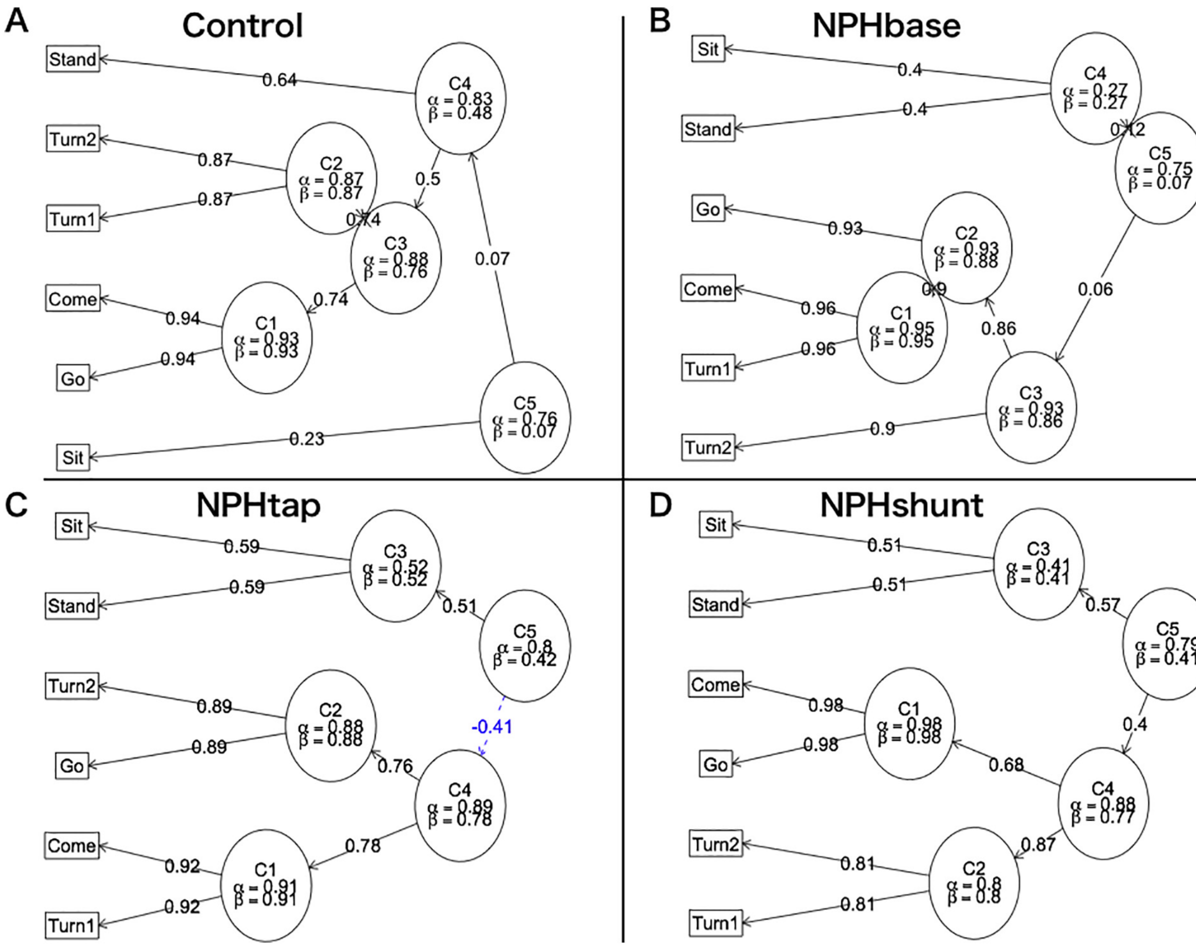

Fig. 3. Item cluster analysis for the control group (A), the baseline of the NPH group (B), the tap test of the NPH group (C) and the shunt surgery of the NPH group (D). Cluster1 included the pair of Go and Come, and Clusters included the pair of Turn1 and Turn2 in the control group (A). This relationship was lost at baseline in the NPH group (B). The pair Turn1 and Come became Cluster 1 at baseline and in the tap test in the NPH group (C). After the surgery (D), the same pattern as that in the control group was restored.

sensors placed at various locations [16]. The iPhone has a three-dimensional accelerometer and gyroscope. Using these sensors, we segmented 6 components of the iTUG automatically by analyzing signal wavelets on the basis of the changes in the angular speeds of the gyroscope [6,7]. Using a similar method with the iPad, Clemens et al. studied the "component-TUG" and reported excellent test-retest reliability in patients with prosthesis after lower limb amputation [17].

This study revealed high correlations only in the pairs of the Go and Come, and Turn1 and Turn2 in the control group. This reflects similarities in straight walk and turn. Although high correlations among the 6 components were also observed in the NPHbase, NPHtap and NPHshunt groups, changes in the gait pattern were not well demonstrated in these groups.

Changes in gait pattern were clearer in the item cluster analysis, which revealed that the pairs of Go and Come, and Turn1 and Turn2 were two major cluster in the control group. In the NPHbase group, this pattern was distorted. In the NPHshunt group, the same pairs as those in the control group were regained. Since shunt surgery is well known to be effective [8,12], recovery of gait pattern after shunt surgery would be due to improvement of brain-CSF interaction including intracranial compliance and drainage of brain waste material.

This study has limitations. A major issue was the failure of segmentation in the wavelet analysis. The algorithm used in this study was similar to those proposed by Salarian et al. [6] and Vervoort et al. [7]. In this study, the segmentation of components often failed in the second session of the iTUG. In the NPHbase and NPHtap groups, the success rates of wavelet analysis in the second session were 50% and 58.3%. In the NPHshunt group, it recovered to 78.9%. The failure of segmentation may be due to the easy fatigability of patients with iNPH. Second, we focused on the gait pattern changes in the patients with iNPH. Patients with other movement disorders may show different characteristics of wavelets and gait patterns.

Using the same iPhone application, Dr. Yamada et al. reported that three-dimensional accelerations are useful for patients with mild gait disturbance. They proposed a novel iTUG score, which consisted of the time and ellipsoid volume for the three-dimensional accelerations in the iTUG [18]. At present, a new version of the free iPhone application named "Hacaro iTUG" is available online. This can provide simple, objective information about various gait disorders.

5. Conclusions

In conclusion, a simple assessment with the iPhone and a free iPhone application enables us to study gait patterns in patients with iNPH. This will be extended to gait analysis in various disorders and age groups.

Acknowledgement

We would like to express thanks to the rehabilitation staffs of the Rakuwakai Otowa Hospital and Rakuwa Villa Ilios for their contribution of data acquisition. We appreciate the Ministry of Health, Labor and Welfare, Japan for their funding support.

Ethical standards

All co-authors have seen and approved this submission. The paper has not been.

previously published. It is not under simultaneous consideration by another journal. There.

was no ghost writing by anyone not named on the author list.

Conflict of interest

MI received speaker's honoraria from Johnson and Johnson, Nihon-Medi-Physics and Medtronic Japan Co., Ltd. (Japan).

SY received speaker's honoraria from Johnson Johnson,Nihon-Med-Physics, Fujifilm Medical systems and Integra Japan.

KY declared no conflicts of interest.

YA declared no conflicts of interest.

Funding sources for the study

This study was partly supported by Health and Labor Sciences Research Grants for the Research on Intractable Diseases, Ministry of Health, Labor and Welfare, Japan (2017-Nanci-General-037). The sponsor was not involved in the study-design, collection, analysis, and interpretation of the data, writing of the report; and in the decision to submit the paper for publication.

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