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ASSESSMENT PROCEDURE

From clinic to smartphone evaluating the i-TUG for balance and fall risk in chronic stroke

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ABSTRACT

Purpose: To determine the test-retest reliability and construct validity of the Instrumental- Timed Up and Go Test (i-TUG), TUG, and Berg Balance Scale (BBS) using EncephaLog in individuals with stroke.

Methods: The study was conducted with 37 individuals diagnosed with chronic ischemic stroke. Participants were assessed using the i-TUG, TUG, BBS, and additional postural sway parameters collected *via* EncephaLog. Two test sessions were conducted to assess test-retest reliability. Pearson correlation coefficients were used to evaluate construct validity, and the Standard Error of Measurement and Minimal Detectable Change (MDC) were also calculated.

Results: High correlation was found between i-TUG and TUG ($r=0.92$; $r=0.70$), and moderate correlation between i-TUG and BBS (r=−0.54; r=−0.63). Postural sway parameters had negligible correlations with BBS and TUG. Test-retest reliability was excellent for i-TUG (ICC = 0.76), TUG (ICC = 0.83), BBS (ICC = 0.88), Time To Stand Up From The Chair (SUT) (ICC = 0.82), and Time To Sit Down On The Chair (SDT) (ICC = 0.79), but poor for Mediolateral Sway (ML_{sway}) (ICC = 0.27) and Anteroposterior Sway (AP_{sway}) (ICC = 0.23). MDC values were as follows: i-TUG (12.36), TUG (9.21), BBS (7.48), ML_{sway} (0.29), AP_{sway} (0.29), SUT (0.57), and SDT (0.51).

Conclusions: EncephaLog-based i-TUG demonstrated high reliability and good validity, comparable to conventional clinical tests in chronic ischemic stroke. While sway parameters showed low correlation and reliability, i-TUG provides a promising, accessible, and objective tool for balance assessment.

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IMPLICATIONS FOR REHABILITATION

- Stroke is one of the leading causes of neurological morbidity and mortality worldwide, and many patients experience walking difficulties and near falls within the first six months after discharge.
- With advancing technology, smartphone applications equipped with motion detection sensors have emerged as feasible, valid, reliable, sensitive, and specific tools for assessing balance in patients post-stroke.
- EncephaLog, one of the smartphone applications, is a valid and reliable tool for assessing balance in individuals with stroke.

Introduction

Stroke is one of the biggest causes of neurological morbidity and mortality worldwide [1]. After stroke, 80% of the patients suffer from walking problems and had experienced near falls [2]. Falls are one of the most common complications following stroke, which ranges from 36% to 73% in the first 6 months post-discharge [3]. During the post-discharge period, nearly one-third of ambulatory stroke patients experience a fall [3,4]. Following falls; soft tissue injuries, fractures, depression, fear of falling and

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inactivity may occur and, worse, increased risk of mortality [4]. Balance loss is known to be a predictor of falls [5], it restricts individuals' independence and participation in daily living activities, thereby reducing their quality of life [6]. Consequently, clinicians are actively seeking new methods to manage balance loss and falls to improve the quality of life for stroke patients [7].

One approach to managing falls is the accurate assessment of balance [8]. Analysis of balance relies on clinical scales and instrumentation, both of which are used to assess balance and determine fall risk in individuals with stroke [9]. The most widely used, easy to implement, low-cost, reliable and valid clinical scales to assess balance in stroke patients are the Timed Up and Go Test (TUG), Berg Balance Scale (BBS), Dynamic Gait Index, Postural Assessment Scale, Fugl-Meyer Assessment Scale, and 2-Minute Walk Test [9–11]. TUG is an objective, simple and quick clinical measure for assessing balance and thus the risk of falling [12]. The TUG measures the time taken for an individual to rise from a chair, walk three meters, turn, walk back and sit down [12]. BBS is one of the most frequently used tools to assess balance and fall risk, consisting of a 14-item scale that evaluates these factors through direct observation of an individual' performance [13]. Ng SS et al. reported that in subjects with chronic stroke, the TUG demonstrated excellent interrater (ICC = 0.99), intrarater reliability (ICC = 0.99), and excellent test-retest reliability (ICC = 0.95). The TUG scores also correlated moderately well with BBS (r=−0.72) in subjects with chronic stroke [14]. Blum et al. reported that in a stroke population, the BBS demonstrated excellent internal consistency (Cronbach's alpha 0.92–0.98), as well as high interrater reliability (ICCs = 0.95–0.98), intrarater reliability (ICC = 0.97), and test-retest reliability (ICC = 0.98) [13]. However, these methods are unable to detect subtle balance changes that could lead to falls [15].

Wearable sensors, including laboratory-based devices with inertial measurement units, are the gold standard instrumental methods for assessing balance [16]. Unlike clinical scales, these devices can detect subtle changes in balance at an early stage [17], however, they are expensive and require training for use [18]. The fact that most falls occur outside of the laboratory and clinical settings has led to the development of instrumental assessment methods that are accessible and usable in daily life, rather than relying on laboratory-based devices [15]. Recent technological advancements have integrated accelerometers, gyroscopes, cameras, global positioning systems, magnetometers, and microphones into smartphones, thereby increasing their utilization in the healthcare sector [19]. Advances in inertial sensor technology have led to increase the availability of portable, cost-effective, and user-friendly applications for everyday use [20,21]. Examples of these include Sway Balance™, SmartMOVE, Roche PD, RUNZI, Fox Wearable Companion, SensorLog, FallSkip, and EncephaLog [22]. Peters et al. demonstrated that smartphone applications like Google Fit, STEPZ, Health and PACER equipped with motion detection sensors are valid, reliable, sensitive, and specific for assessing balance post-stroke [15]. Four studies revealed that smartphone applications have excellent reliability (ICC = 0.76–0.99) during gait and balance assessments in stroke patients [20,23–25].

EncephaLog (by Mon4t® Brain Monitor, Tel-Aviv, Israel) is a smartphone application capable of assessing motor functions using the inertial systems of smartphones [26]. It determines balance and fall risk through its instrumental-TUG (i-TUG), which provides quantitative data [26]. EncephaLog records changes in center of pressure sway (mediolateral, anteroposterior) to assess postural instability, as well as the times taken to stand up from and sit down on a chair during the i-TUG [26]. The EncephaLog was also validated against other standard methods used in clinics and motion labs for quantitative TUG analysis, such as a stopwatch [27], force treadmill, wearable sensors, and 3D motion capture system [26]. In a study by Yahalom et al. which compared i-TUG with the standard TUG in patients with Parkinson's disease (PD), it was concluded that wearable sensor-based technologies offer more sensitive and quantitative results for balance assessment than standard clinical tests [28]. i-TUG was found to have higher accuracy and sensitivity compared to qualitative measures, and it was also useful in predicting fall risk in PD [29,30]. Although previous studies using EncephaLog have demonstrated the usability of i-TUG in patients with PD [28,31], its effectiveness in stroke patients is still unknown. The study primarily aims to assess the test-retest reliability and validity of the i-TUG, standard TUG, and BBS using the EncephaLog system in individuals with chronic ischemic stroke. It also seeks to explore the relationship between EncephaLog-derived kinematic data and conventional TUG and BBS outcomes, and to establish the minimal detectable change (MDC) for these measures.

Methods

Study design

This observational study was designed to evaluate the reliability and validity of the i-TUG in stroke patients by comparing it with the conventional TUG and BBS. The study was conducted at the Stroke Outpatient Clinic of Istanbul Aydin University, Medical Park Hospital, between October 2024 and March 2025. All patients who volunteered to participate in the study were given a written and verbal explanation about the purpose of the study and the procedures to be applied. Patients are usually admitted in chronic stage after stroke. In the study conducted in accordance with the Declaration of Helsinki, the rights of the volunteers were protected by signing informed consent forms if the patient agreed to participate. The study protocol was approved by the Ethics Committee of Clinical Research, Bezmiâlem Vakıf University (No: E-54022451-050.04-171654).

Participants

Participants were included in the study if they met the following criteria: voluntary participation; a confirmed diagnosis of ischemic stroke based on MRI or CT scan and in the chronic phase (≥ 6 months post-stroke); no involvement in any physiotherapy program for at least three months prior to the study; age between 18 and 75 years; a Mini-Mental State Examination (MMSE) score of ≥ 24; the ability to walk independently (Functional Ambulation Scale [FAS] score > 3) and to walk 10 meters with or without an assistive device; and gastrocnemius muscle spasticity graded as 2 or less on the Modified Ashworth Scale (MAS). Participants were excluded if they had severe visual or cognitive impairments, severe cardiovascular disease, or musculoskeletal conditions or skin disorders that affected the lower extremities.

Procedures

The assessments (i-TUG, TUG, or BBS) were conducted by the same physical therapist in a face-to-face manner. Prior to assessments, participants received detailed information about the study and rested for 30 min. The order of assessments was determined using an online computer-based randomization tool (http://www.randomization.com). To minimize order effects, participants were given a 5-min rest between tests; however, potential order effects among the tests conducted on the same day were not formally assessed. Each participant was assigned a number corresponding to one of the assessment methods. To eliminate potential learning effects and assess concurrent validity, there was a 7-day interval between the tests [9]. The i-TUG, TUG, and BBS assessments were conducted on the same day and repeated after seven days. Each session took about 20–25 min and was performed at the same time of day in a clinical setting on a flat surface.

Instrumental-timed up and go test (i-TUG)

EncephaLog is an FDA-cleared, smartphone-based application designed to assess dynamic balance and gait disorders in older adults and individuals with neurological or non-neurological conditions. The application uses the smartphone' built-in accelerometer and gyroscope to deliver reliable and valid kinematic assessments. The smartphone (iphone) was securely placed on the participant's sternum with an elastic belt. After a 5-s countdown with audio and vibration cues, participants stood up, walked 3 meters to a cone, turned around it, walked back, and sat down. The participants were instructed to perform this task as fast as possible without running. The application provided objective and quantitative data by recording total walking time, time to stand up from the chair (SUT), time to sit down on the chair (SDT), as well as mediolateral sway (ML_{sway}) and anteroposterior sway (AP_{sway}) [22,27].

Timed up and go test (TUG)

TUG test is a commonly used and validated measure to assess balance and mobility. Initially developed for older adults [32], it has since been widely adopted for neurological and pediatric populations [33–35]. The test requires the participant to rise from a chair, walk 3 meters, turn, walk back and sit down. The time to complete the task is recorded. A score greater than 13.5 s indicates an increased risk of falling in elderly [36]. The test has shown excellent intra-rater reliability in stroke patients, with ICC values ranging from 0.95 [14] to 0.96 [37] and a standard error of measurement (SEM) of 1.16. MDC was reported as 3.2 s in chronic stroke patients [9]. The minimal clinically important change (MCID) of the TUG in stroke patients is still unknown.

Berg Balance Scale (BBS)

The BBS consists of 14 items designed to assess postural control and fall risk in elderly individuals [38]. Tasks include sitting to standing, standing unsupported, transfers, turning, and stepping. Each item is scored from 0 to 4, and the total score ranges from 0 to 56. A score between 0–20 indicates high fall risk and need for assistive devices; 21–40 indicates moderate fall risk; and 41–56 indicates low fall risk with no need for assistive devices [13]. The BBS has been validated and found to be appropriate for balance assessment in individuals with stroke [39]. The BBS has demonstrated excellent internal consistency (Cronbach's alpha= 0.92–0.98), inter-rater reliability (ICC = 0.95–0.98), intra-rater reliability (ICC= 0.97), and test-retest reliability (ICC= 0.98). The SEM was 0.98, and the MDC was 2.7 in chronic stroke patients [9].

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics version 26 (IBM SPSS, Turkey). The Shapiro-Wilk test was used to assess the normality of data distribution. Agreement between the i-TUG, TUG, and BBS tests was assessed using the two-way random-effects intraclass correlation coefficient (ICC [ρ]). Reliability was interpreted as follows: $\rho < 0.40$ (poor), 0.40–0.75 (moderate to good), and >0.75 (excellent) [40]. Agreement between two measurements of each scale was assessed using the Bland-Altman method. In this method, the mean of the scores was plotted on the x-axis, and the difference between the scores on the y-axis. The 95% limits of agreement were calculated by adding and subtracting 1.96 times the standard deviation of the differences from the mean difference. This range indicates where approximately 95% of the differences between the two methods are expected to lie, assuming normal distribution [41]. The SEM was calculated using the following formula: $SEM = SD \times \sqrt{(1 - ICC)}$ [42]. The MDC was calculated as: $MDC = 1.96 \times \sqrt{2} \times SEM$ [43]. Pearson correlation coefficients were also used to evaluate validity, and were interpreted as follows: very high (0.90–1.00), high (0.70–0.90), moderate (0.50–0.70), low (0.30–0.50), and negligible (0.00–0.30) [44]. Additionally, an intention-to-treat analysis was conducted for the five participants who did not complete the second assessment. Missing follow-up data were addressed using multiple imputation in SPSS (Analyze, Multiple Imputation, Impute Missing Data Values); five datasets were generated under the assumption of missing at random using fully conditional specification, and the results were pooled according to Rubin's rules for the final analyses.

Results

A total of 43 patients were screened for eligibility. Of these, six patients did not meet the inclusion criteria and were excluded from the study. Specifically, three patients were excluded due to a spasticity level greater than 2 on the MAS, and three patients due to a FAS score of less than 3. Ultimately, 37 patients were included in the study. No adverse effects were reported by any of the participants. Five participants did not attend the second assessments, and statistical analysis was performed using the intention-to-treat approach. The study included 37 patients, of whom 23 were male and 14 were female. The mean age of the participants was 62.02 ± 9.65 years. The mean body mass index was 26.88 ± 4.03. The affected side was the right in 19 patients and the left in 18 patients. The mean duration since stroke onset was 9.68 ± 7.61 months. Regarding stroke type, all patients had ischemic stroke ($n = 37$); no cases of hemorrhagic stroke were observed. Table 1 details the demographic data and stroke-related characteristics.

There were no significant differences in the mean total i-TUG score, total TUG score, ML_{sway}, AP_{sway}; but there were significant differences in the mean total BBS score, SUT and SDT scores between measurements (Table 2).

Table 1. Participant's characteristics.

	Mean ± SD or N $N = 37$
Sex, Male/Female	23/14
Age, Years	62.02 ± 9.65
BMI, kg/m^2	26.88 ± 4.03
Affected Side, Right/Left	19/18
Duration Since Onset, Months	9.68 ± 7.61
Stroke Type, Ischemic/Hemorrhage	37/0

SD, Standard Deviation; N, Number; BMI, Body Mass Index; kg, kilogram; m^2, square meters.

Table 2. Test-retest scores for the i-TUG, TUG, BBS, and EncephaLog parameters.

	Mean ± SD	Range (min-max)	*p - value
i-TUG$_1$	23.03 ± 12.01	7.87-70.0	0.98
i-TUG$_2$	23.07 ± 8.37	11.00-41.03	
TUG$_1$	24.42 ± 12.59	0.00-70.0	0.13
TUG$_2$	22.33 ± 9.03	0.00-39.63	
BBS$_1$	36.27 ± 13.17	4.00-56.0	**<0.001**
BBS$_2$	41.29 ± 10.73	14.00-56.0	
ML$_{sway1}$	0.07 ± 0.05	0.01-0.21	0.17
ML$_{sway2}$	0.10 ± 0.12	0.00-0.67	
AP$_{sway1}$	0.12 ± 0.1	0.02-0.5	0.35
AP$_{sway2}$	0.10 ± 0.07	0.01-0.29	
SUT$_1$	1.97 ± 0.66	0.92-3.46	**<0.001**
SUT$_2$	1.71 ± 0.57	0.91-2.93	
SDT$_1$	1.77 ± 0.48	0.97-3.44	**<0.001**
SDT$_2$	1.57 ± 0.48	1.01-3.26	

*p, Paired samples test based on intention to treat analysis-pooled data.

Table 3. Concurrent validity of EncephaLog parameters, TUG, and BBS scores at day 1 and day 7.

	i-TUG vs BBS	i-TUG vs TUG	ML$_{sway}$ vs BBS	ML$_{sway}$ vs TUG	AP$_{sway}$ vs BBS	AP$_{sway}$ vs TUG	SUT vs BBS	SUT vs TUG	SDT vs BBS	SDT vs TUG
r$_1$	−0.54	0.92	0.00	0.08	0.07	0.01	−0.05	0.11	−0.16	0.52
(Day 1) (95% CI)	(−0.85-(−0.36))	(0.80–0.98)	(−0.33-0.35)	(−0.23-0.46)	(−0.27-0.35)	(−0.19-0.33)	(−0,27-0.35)	(−0.21-0.37)	(−0.39-0.11)	(0.04–0.77)
p[a]	**<0.001**	**<0.001**	0.98	0.64	0.66	0.91	0.76	0.51	0.32	**<0.001**
r$_2$	−0.63	0.70	0.19	−0.18	0.21	0.03	−0.05	0.08	−0.18	0.21
(Day 7) (95% CI)	(−0.80-(−0.44))	(0.40–0.95)	(−0.12-0.61)	(−0.57-0.04)	(−0.18-0.49)	(−0.34-0.44)	(−0.37-0.32)	(−0.25-0.41)	(−0.32-0.15)	(−0.09-0.50)
p[a]	**<0.001**	**<0.001**	0.26	0.32	0.19	0.63	0.73	0.66	0.28	0.23

[a]Pearson correlation analysis was performed to assess the concurrent validity between EncephaLog and BBS scores at Day 1 and Day 7.
i-TUG, Instrumental Timed Up And Go Test by Encephalog; TUG, Conventional TUG; BBS, Berg Balance Scale; ML$_{sway}$, Mediolateral Sway; AP$_{sway}$, Anteroposterior Sway; SUT, Stand Up Time; SDT, Sit Down Time; CI, Confidence Interval.

A high level of correlation was found between the i-TUG and TUG (r_1=0.92, $p < 0.001$; r_2=0.70, $p < 0.001$). A moderate correlation was observed between the i-TUG and BBS ($r_1 = -0.54$, $p < 0.001$; $r_2 = -0.63$, $p < 0.001$). The correlations of ML$_{sway}$, AP$_{sway}$, SUT, and STD with BBS and TUG were found to be low negligible. Pearson correlation coefficients for each parameter are detailed in Table 3.

Test-retest reliability was found excellent for i-TUG (0.76), TUG (0.83), BBS (0.88), SUT (0.82), and SDT (0.79). In contrast, ML$_{sway}$ (0.27) and AP$_{sway}$ (0.23) showed poor reliability. The SEM values for i-TUG, TUG, BBS, ML$_{sway}$, AP$_{sway}$, SUT, and SDT were calculated as 4.46, 3.32, 2.70, 0.11, 0.11, 0.21, and 0.18, respectively. The corresponding MDC values were 12.36, 9.21, 7.48, 0.29, 0.29, 0.57, and 0.51, respectively. Detailed values for each parameter are presented in Table 4.

Bland-Altman analyses were also performed to determine reliability for the parameters. The 95% limits of agreement were calculated as follows: for i-TUG, −17.79 to 17.87; for TUG, −18.11 to 13.47; for BBS, 10.24 to 20.29; for SUT, −1.20 to 0.68; for SDT, −0.98 to 0.58; for ML$_{sway}$, −0.21 to 0.27; and for AP$_{sway}$, −0.25 to 0.21. The Bland-Altman limits of agreement for each parameter are presented in Figure 1 Bland-Altman Plot of the Instrumental Timed Up and Go Test (i-TUG), SUT, SDT, ML$_{sway}$, and AP$_{sway}$, Figure 2 Bland-Altman Plot of the Timed Up and Go Test (TUG), and Figure 3 Bland-Altman Plot of the Berg Balance Scale (BBS) indicating a reasonable agreement between the test and retest scores for each measure.

Table 4. ICCs, Confidence Intervals, Standard error of measurement (SEM), and minimal detectable change (MDC) of the i-TUG, TUG, BBS, and EncephaLog parameters.

Variables	ICC (95% CI)	SEM	MDC
i-TUG	0.76 (0.53–0.87)	4.46	12.36
TUG	0.83 (0.68–0.91)	3.32	9.21
BBS	0.88 (0.77–0.94)	2.70	7.48
ML_{sway}	0.27 (−0.4 – 0.62)	0.11	0.29
AP_{sway}	0.23 (−0.49 – 0.6)	0.11	0.29
SUT	0.82 (0.65–0.9)	0.21	0.57
SDT	0.79 (0.59–0.89)	0.18	0.51

i-TUG, Instrumental Timed Up and Go Test by Encephalog; TUG, Conventional TUG; BBS, Berg Balance Scale; ML_{sway}, Mediolateral Sway; AP_{sway}, Anteroposterior Sway; SUT, Stand Up Time; SDT, Sit Down Time; ICC, Intraclass Correlation Coefficient; SEM (SD × $\sqrt{(1-\text{ICC})}$), Standard error of measurement; MDC, Minimal Detectable Change; CI, Confidence Interval.

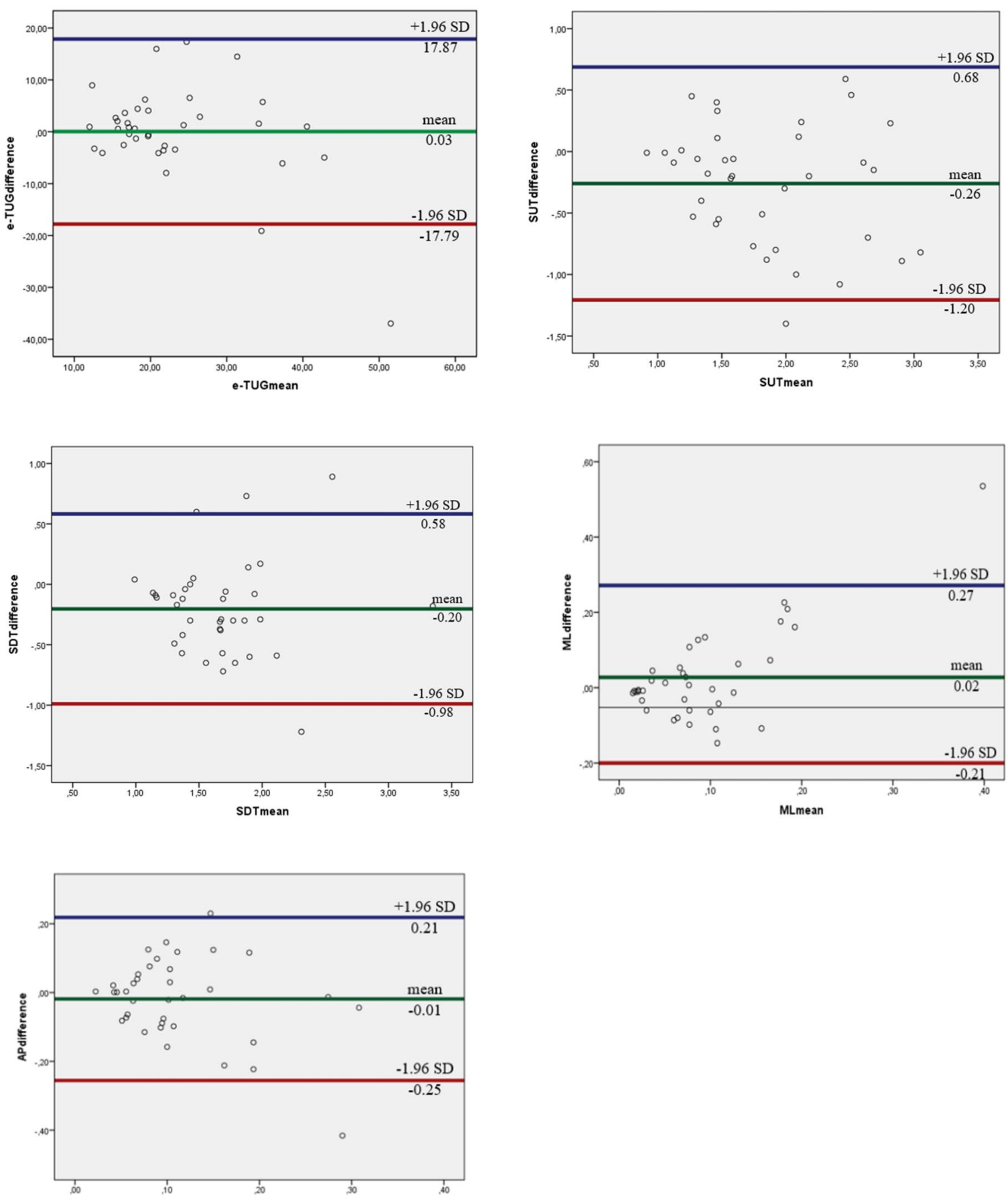

Figure 1. Bland-Altman plot of the instrumental timed up and go test (i-TUG), SUT, SDT, ML_{sway}, and AP_{sway}.

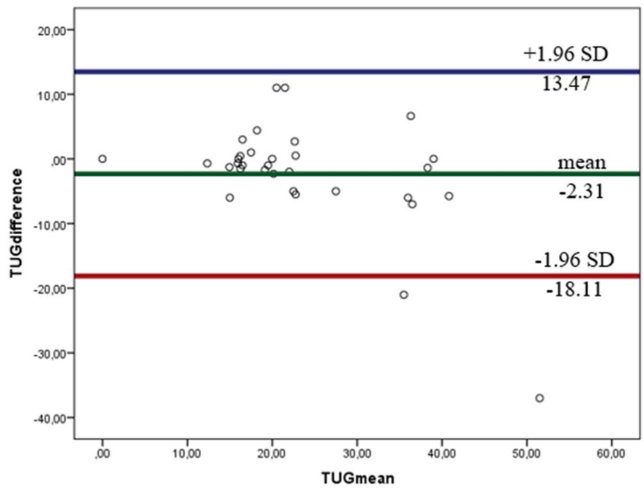

Figure 2. Bland-Altman plot of the Timed Up and Go Test (TUG).

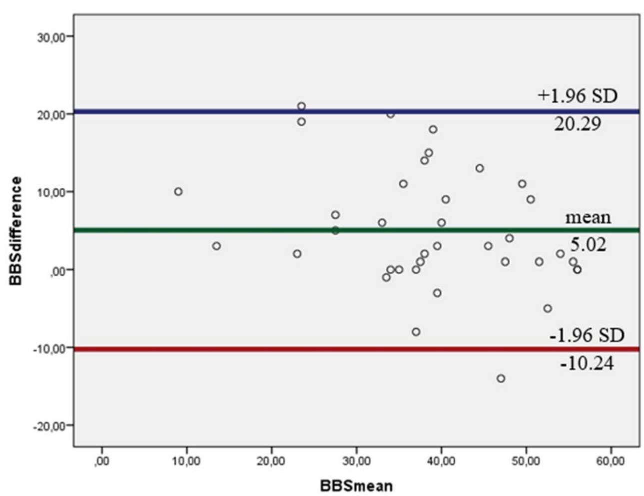

Figure 3. Bland-Altman plot of the Berg Balance Scale (BBS).

Discussion

Balance impairments are associated with increased fall risk and reduced quality of life in individuals with stroke. Effective assessment of these impairments in both home and clinical settings may help reduce fall risk and improve functional outcomes. Reliable and valid measurement tools are essential to be able to follow changes over time or after an intervention in patients with chronic ischemic stroke. In this study, the reliability, validity, SEM, and MDC of the i-TUG, TUG, and BBS were evaluated for assessing balance and fall risk in patients with chronic stroke. The findings revealed a high correlation between i-TUG and the standard TUG, and a moderate correlation with the BBS, supporting the construct validity of the i-TUG in evaluating functional mobility and balance. Test-retest reliability was excellent for i-TUG, TUG, BBS, SUT, and SDT, indicating consistent measurement across time. However, the relatively poor reliability observed in ML_{sway} and AP_{sway} parameters suggests these components may be more sensitive to external factors or measurement error and should be interpreted with caution. The calculated MDC values indicate that i-TUG can detect meaningful changes over time.

According to Peters et al. smartphone applications incorporating accelerometers and gyroscopes are effective in accurately assessing post-stroke balance [15]. BBS and TUG are the most commonly used outcome measures in patients with chronic stroke. BBS is used to assess static and dynamic balance and risk of falling; TUG is used to evaluate sitting balance, transfers from sitting to standing, stability during gait pattern and transfers in patients with stroke. BBS and TUG have been validated and have also been found suitable for assessing balance in individuals with stroke [9]. However, BBS and TUG are objective measurement methods for assessing balance and determining fall risk in individuals with stroke, they are not as precise as accelerometers and gyroscopes that provide quantitative data [27]. In this study, the correlation of i-TUG with TUG and BBS, as well as the test-retest reliability, SEM, and MDC values of the tests were calculated in patients with chronic ischemic stroke. It was found that i-TUG showed a high correlation with TUG and a moderate correlation with BBS. The test-retest reliability of i-TUG, TUG, BBS, SUT, and SDT was found to be excellent (ICC ≥0.75). According to the Bland-Altman analysis, all measurements were determined to be reasonable. Findings suggest that the strong correlation between i-TUG and TUG supports the use of i-TUG as a tool for providing more objective data in clinical practice. However, compared with i-TUG, the BBS offers a more comprehensive assessment by evaluating balance across a variety of functional activities. Therefore, when the goal is to assess balance during diverse tasks, the BBS is more advantageous than either i-TUG or TUG. However, the BBS requires a longer administration time compared with both TUG and i-TUG. Overall, when clinical time is limited and the primary goal is to assess fall risk, i-TUG can serve as a more efficient and practical tool.

In their research, Yahalom et al. analyzed objective gait and balance metrics in individuals with psychiatric disorders undergoing antipsychotic therapy. The study concluded that wearable sensor-based technologies for assessing gait and balance may serve as a more sensitive and quantitative tool for detecting clinical features of neuroleptic-induced parkinsonism compared to standard clinical rating scales [28]. In another study conducted by Yahalom et al. the feasibility of the smartphone-based EncephaLog application was investigated to assess postural instability and gait impairments in individuals with PD. The study concluded that sensor data obtained from smartphones could serve as a sensitive and quantitative tool for detecting gait and balance differences in patients with PD [31]. Inbar et al. conducted a feasibility study to evaluate gait disturbances in individuals with Huntington's disease (HD) using the EncephaLog, in which participants completed TUG tests while movement data were collected *via* the smartphone's built-in accelerometer and gyroscope. Data from HD patients demonstrated significant correlations between various gait parameters and clinical scores of dyskinesia. Despite the presence of dyskinesia and cognitive impairments, participants were able to complete the assessments successfully. The results suggest that the EncephaLog is a sensitive, quantitative, and practical tool for assessing gait in HD [45]. In line with previous studies in neurological and psychiatric populations, the present study used the EncephaLog to assess balance in individuals with stroke. Findings suggest that, similar to its use in conditions such as PD and HD, EncephaLog is a valid, reliable, and practical tool for evaluating balance in stroke patients. Its ability to provide quantitative data makes it a suitable option for both clinical assessment in stroke.

A study by Hou et al. explored the practicality of using a smartphone-based system to assess balance in individuals with chronic stroke. Using the built-in accelerometer and gyroscope of an HTC smartphone, balance data were collected during six standing postures under eyes-open and eyes-closed conditions. The study included 10 stroke patients and 13 healthy controls. Significant differences in balance performance were found between the groups, particularly in more challenging postures. The findings suggest that smartphone sensors can provide a simple, valid, and practical tool for assessing balance in individuals with chronic stroke [46]. Gait and balance dysfunctions have been highlighted in a systematic review as primary contributors to fall risk and decreased quality of life among stroke survivors. The review emphasizes the importance of accurately assessing these impairments in both clinical and home settings to help reduce fall risk and improve functional outcomes. Findings support that smartphone-based applications are valid, reliable, sensitive, and specific tools for gait and balance assessment. These technologies have demonstrated their feasibility and effectiveness, particularly in laboratory settings, for use in individuals with stroke [15].

In this study, test-retest reliability was found excellent for i-TUG (0.76), TUG (0.83), BBS (0.88), SUT (0.82), and SDT (0.79). In contrast, ML_{sway} (0.27) and AP_{sway} (0.23) showed poor reliability. The test-retest reliability of the present TUG and BBS was similar to previous findings in individuals with stroke [9,11,47]. The poor reliability observed in ML_{sway} and AP_{sway} may be related to the dynamic nature of the i-TUG task, as these parameters were obtained during movement rather than steady standing. Sway measures are highly sensitive to slight variations in trunk alignment, sensor placement, and attentional focus, which can increase signal noise and reduce reproducibility. Additionally, the heterogeneity in motor control strategies among individuals with chronic stroke may have contributed to variability. Therefore, the low ICCs likely reflect measurement sensitivity under dynamic conditions rather than device-related error. The significant improvements in BBS, SUT, and SDT between sessions likely reflect a learning or familiarization effect, as participants became more accustomed to the testing procedures. Similar practice-related changes have been reported in previous studies, suggesting these differences are procedural rather than clinical.

In the study by Hiengkaew et al. [11], individuals with chronic stroke and varying ankle plantarflexor tone were included, and the absolute and relative MDC values for each measure were determined. The MDC value was found to be 5 points for the BBS and 8 s for the TUG. In this present study, the MDC values was found to be 12.36 for i-TUG, 9.21 for TUG and 7.48 for BBS. Unlike the study by Hienkaew et al. the MDC values in this present study are higher. The previous study included 61 participants with both ischemic and hemorrhagic stroke, with a mean post-stroke duration of 40.22 ± 34.3 months. In contrast, in this present study included 37 participants with only ischemic stroke patients, with an average post-stroke duration of 9.68 ± 7.61 months. The MDC values obtained in this study (12.36 s for i-TUG, 9.21 s for TUG, and 7.48 points for BBS) represent the minimal changes required to indicate true performance improvement beyond measurement error. Although slightly higher than previous reports, these values are clinically acceptable given the smaller sample size and variability among chronic stroke participants, and may serve as preliminary reference thresholds for detecting meaningful change in this population. There is no existing study that provides test-retest reliability and MDC data for the EncephaLog i-TUG, SUT, SDT, ML_{sway}, and AP_{sway} parameters in patients with chronic stroke. This study is the first to present such data. Bland-Altman analyses were also performed to determine reliability for the parameters.

In the present study, the SEM values of i-TUG, TUG, BBS, SUT, SDT, ML_{sway}, and AP_{sway} were 4.46, 3.32, 2.70, 0.21, 0.18, 0.11, and 0.11. The SEM value of i-TUG test was slightly higher than the total TUG scores (4.46 vs. 3.32) and the total BBS scores (4.46 vs. 2.70) in patients with chronic ischemic stroke. Flansbjer et al. [48], reported a lower SEM for total BBS scores compared to our study (1.49 vs. 2.70), while Hiengkaew et al. [11], found a similar SEM for the TUG test than ours (3.22 vs. 3.32). In the present study, the SEM values for all parameters were found to be low, indicating high measurement precision and minimal random error. These findings suggest that the tests and measurements used in this study have high absolute reliability in individuals with chronic ischemic stroke. The low SEM values further support the consistency of the assessments and demonstrate that the observed scores are close to the participants' true scores, rather than being influenced by measurement variability. Particularly in clinical settings, where even small changes in performance may influence clinical decisions, the low SEM values enhance the utility of these tools for both initial assessment and follow-up evaluations. Therefore, these results confirm the suitability of the i-TUG, TUG, BBS, and the parameters measured *via* EncephaLog for reliable use in stroke rehabilitation monitoring.

In the study by Inbar et al. [45], despite cognitive issues and symptoms like chorea in individuals with HD, participants showed good compliance with smartphone-based assessments. Significant correlations were found between EncephaLog outputs and Gait UHDRS scores (rotation time: $r = 0.72$, $p = 0.0001$; sit-down time: $r = 0.52$, $p = 0.011$; medio-lateral sway: $r = 0.45$, $p = 0.032$). Similarly, in this present study, despite physical limitations in chronic stroke patients, a strong correlation was found between i-TUG and TUG (r_1 = 0.92; r_2 = 0.70), and a moderate correlation was observed between i-TUG and BBS (r_1 = −0.54; r_2 = −0.63). The correlations of ML_{sway}, AP_{sway}, SUT, and SDT with BBS and TUG were low or negligible.

One of the strengths of this study is that it focused solely on chronic ischemic stroke patients, creating a homogeneous patient group that allowed for reliable results. Additionally, the correlation between EncephaLog i-TUG and traditional balance tests highlights the potential use of mobile applications in clinical assessments. This study presents a novel approach in clinical practice by demonstrating the applicability of smartphone-based evaluations for monitoring balance functions. The high test-retest reliability and stable test durations further support the suitability of mobile technologies for objective and reproducible measurements. Finally, the study results provide a valuable guide for improving methods of monitoring motor function in chronic stroke patients and contribute to the practical application of current tests.

This study has several limitations that should be acknowledged. First, participants were selected based on specific functional criteria; only those with a FAS score greater than 3 and a MAS score less than 2 were eligible. This inclusion criterion may have resulted in a sample with relatively better functional status and limited spasticity, thereby restricting the applicability of the results to individuals with more severe motor impairments. Second, only 37 participants were included, and this small sample size limits the generalizability of the findings. Third, the effects of sex were not examined, and no data were available regarding stroke lesion localization, which could potentially influence balance and gait outcomes.

In conclusion, this study demonstrates that smartphone-based assessments, such as EncephaLog, can provide reliable and valid measurements of balance in chronic ischemic stroke patients. Strong correlations with the traditional TUG and moderate associations with BBS support its clinical relevance. While most parameters showed good test-retest reliability, ML_{sway} and AP_{sway} had limited consistency. The calculated MDC values indicate that i-TUG can detect meaningful changes over time. EncephaLog uses the smartphone's accelerometer and gyroscope to record three-dimensional movements, which its algorithms convert into measures such as postural sway. This allows accurate, real-time balance assessment without special equipment. Its portability and low cost make it practical for routine follow-up, home rehabilitation, and community screening. This study is among the first to validate smartphone-based i-TUG in a homogeneous group of chronic ischemic stroke patients, emphasizing the system's originality and clinical relevance. Future research should focus on validating the i-TUG in larger and more heterogeneous populations, incorporating advanced biomechanical tools, and exploring its responsiveness to rehabilitation interventions.

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Author contributions

CRediT: **Rustem Mustafaoglu**: Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing; **Ibrahim Halil Ural**: Investigation, Methodology, Supervision.

Consent statement

Ethical review boards from all sites approved the study protocol and all participating individuals provided written and informed consent in agreement with the Declaration of Helsinki. The study protocol was approved by the Ethics Committee of Clinical Research, Bezmiâlem Vakıf University (No: E-54022451-050.04-171654).

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Data availability statement

The datasets generated the current study are available from the corresponding author on reasonable request.

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