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Research Article

AppTUG - A Smartphone Application of Instrumented 'Timed Up and Go' for Neurological Disorders

Gilad Yahalom[1,2]*, Ziv Yekutieli[3], Simon Israeli-Korn[1], Sandra Elincx-Benizri[1], Vered Livneh[1], Tsviya Fay-Karmon[1], Yarin Rubel[4], Keren Tchelet[3], Jacob Zauberman[5] and Sharon Hassin-Baer[1,2]

[1]The Movement Disorders Institute, Department of Neurology and Sagol Neuroscience Center, Chaim Sheba Medical Center, Tel-Hashomer, Israel

[2]Sackler Faculty of Medicine, Tel Aviv University, Tel Aviv, Israel

[3]Montfort Brain Monitor LTD, Zichron Yaakov, Israel

[4]Afeka College, Tel-Aviv, Israel

[5]The Pediatric Neurosurgery Unit and the Department of Neurosurgery, Chaim Sheba Medical Center, Tel-Hashomer Israel

***Corresponding Author:** Gilad Yahalom, The Movement Disorders Institute, Department of Neurology and Sagol Neuroscience Center, Chaim Sheba Medical Center, Tel-Hashomer, Israel.

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Abstract

Background: The Timed Up and Go (TUG) test is a simple and commonly used test for evaluating balance function and walking ability in the elderly and in patients with gait disorders due to neurological or non-neurological diseases. The only outcome measure of the TUG test is the completion time, which is taken manually by the clinician using a stopwatch. The start time and end time are subject to observer bias and error. Recent studies show that smartphones' integral sensors have sufficient reliability and validity for evaluation of kinematic tests. By using a smartphone, we can conduct the TUG test more accurately, providing more information and potentially discriminating among different clinical conditions.

Objectives: To provide a preliminary validation for a smartphone-based instrumental TUG, by comparing its measurements to the stopwatch-measured TUG completion time, and to explore its potential and usability for a more detailed analysis of TUG tests. Methods: 25 healthy elderly subjects (HC, age: 69.3 ± 4.6 years), 25 patients with normal pressure hydrocephalus (NPH, age: 72.8 ± 4.7 years) and 15 patients with Parkinson's disease (PD, age: 69.3 ± 4.4 years) were enrolled in the study and performed both the 3-meter and the 10-meter TUG. Subjects were monitored by an iPhone attached to their sternum by means of a strap, while running "AppTUG" - a specially designed application for TUG recording. In parallel, subjects were timed by using a stopwatch.

Methods: 25 healthy elderly subjects, 25 patients with normal pressure hydrocephalus (NPH) and 15 patients with Parkinson's disease (PD) were enrolled in the study and performed both the 3-meter and the 10-meter TUG. Subjects were monitored by an iPhone attached to their sternum by means of a strap, while running "AppTUG" - a specially designed application for TUG recording. In parallel, subjects were timed by using a stopwatch.

Results: A high correlation was found between the TUG completion time recorded by the stopwatch and AppTUG ($r = 0.98$) from the NPH patients. PD and NPH patients showed a similarly longer TUG completion time as compared to HC. The NPH group showed significantly longer standing-up interval (3.9 ± 1.8 seconds) ($p < 0.01$) as compared to both the PD (2.2 ± 0.6 seconds) and the HC (1.8 ± 0.2 seconds) groups, and had a significantly longer sitting down time (4.7 ± 2.4 seconds) as compared to PD patients (3.2 ± 1.8 seconds) ($p < 0.01$) who were significantly slower than the HC (2.5 ± 0.4 seconds) ($p < 0.05$).

Discussion: AppTUG provides accurate TUG completion time. Furthermore, the timing of the standing-up and sitting-down segments differed between PD, NPH and HC. Using AppTUG turns a standard smartphone into an inexpensive, compact, accessible and user-friendly instrument that can be used for evaluating gait and balance in the clinic and potentially in the patient's natural environment as well.

***Keywords:** AppTUG; Timed Up and Go (TUG)*

Background

Gait and posture have been traditionally assessed using functional gait and balance scales, quantitative (platform) posturography and, in recent years, by computerized motion analysis systems, based on sensors and video recordings. Postural sway and other important parameters of balance function, have been analyzed for clinical and research purposes in a variety of vestibular, musculoskeletal, central and peripheral nervous system disorders [1]. There is no single tool that can evaluate all aspects of balance control, and the type of assessment, selected by the clinician, depends on the purpose of the assessment and on the type of balance deficits to be evaluated. Several existing tools are relatively expensive, difficult to implement and require a large space to operate. Thus, they are usually only used for laboratory research and not for clinical purposes. As a result, most physicians still perform motor assessment by a subjective visual inspection and clinical scales.

The Timed Up and Go test (TUG) is one of the most commonly used clinical test for mobility and balance assessment. TUG is a simple, quick and validated test that was initially introduced to assess functional mobility in the elderly [2] and in patients during rehabilitation [3]. In this test, the subject is instructed to stand up from a chair, walk 3 meters, turn back, walk 3 meters and sit down in the chair. TUG is limited as it measures only test completion time (by a stopwatch), and requires the attention of a supervisor. It has been suggested that different impairments obtained from the TUG may provide a more complete set of parameters to assess characteristics and risk of falling [4,5].

Researchers have attempted to expand the clinical data obtained from the TUG, developing platforms for an instrumental TUG to supplement the quantitative information with automatic detection and separation of subcomponents; these groups used either a setup of seven inertial sensors (a combination of accelerometers and gyroscopes) attached on the forearms, shanks, thighs and sternum, a single portable tri- axial accelerometer worn on the lower back, or an Inertial Measurement Unit consisting of a tri-axial accelerometer and gyroscope sensor fixed with an elastic belt at the level of lumbar spine. With these instrumental TUG platforms, hese studies succeeded in discriminating between healthy controls and patients with Parkinson's disease (PD) [6] and in the latter case between young and older adults [7]. Smartphones are cellular phones that have computing power, graphics and user- interface capabilities, internet access and include the ability to run specialized programs (Apps), which can be downloaded from a variety of sources. Additionally, many smartphones include an array of internal sensors among which accelerometers, gyroscopes, a compass and a global positioning system (GPS) that provide information on acceleration and rotation (in all axes), orientation and position, respectively. These technological capabilities, when combined with smartphone availability, make them good candidates to be used as a medical device in the clinic, and for monitoring patients at their home. Recent studies, have demonstrated that smartphones can sample human acceleration during kinematic tests, with similar reliability and validity as products specially designed for this purpose [8-10] and have suggested using the smartphone for instrumenting the TUG [9].

In this study, we present a new smartphone-based instrumental TUG application called "AppTUG", which manages the TUG routine and provides TUG completion time, along with several sub-components of the TUG, such as standing up and sitting down times. In this study, we aimed to test the usability and validity of AppTUG on 2 common clinical conditions: normal pressure hydrocephalus (NPH) and PD as well as normal ageing. We measured the accordance between the standard method for measuring TUG completion time (by a supervisor using a stopwatch) to that measured by AppTUG, in order to validate AppTUG accuracy.

Methods

The equipment

AppTUG (by Montfort®) runs on Apple's mobile Operating System (iOS) and Android devices and is available for use from the App store. For this study, we used iPhone4, (Apple®, Cupertino, California, USA). The device is 115.2 x 58.6 x 9.3 mm. Similar results were obtained on iPhone5, 6, and several Android based devices (LG, Samsung and others). The device was attached to the subject's sternum by means of a flexible strap. AppTUG utilizes a three-axis accelerometer, a three-axis gyroscope and a magnetometer (compass). AppTUG samples the sensors at a frequency of 100Hz, providing high temporal resolution. The raw accelerometer output was processed through high and low-pass filters to minimize jitter and account for gravity. The TUG procedure, as captured by AppTUG, is shown in figure 1 which presents two sensors out of AppTUG output: one accelerometer axes and one gyroscope.

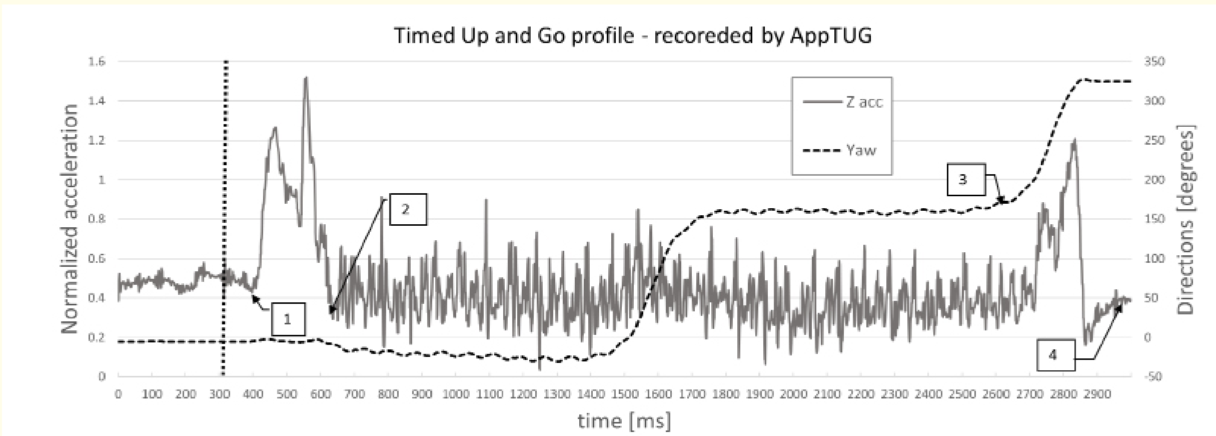

Figure 1: *One accelerometer and one gyroscope as captured by AppTUG. The vertical dashed line indicates the Start signal. We can notice the stand-up time (SUT) between 1 and 2, each step in either direction, rotation circa 1.5 seconds, and sit-down time (SDT) between 3 and 4. Data is sampled at 100Hz, time is in milliseconds.*

Prior to the test initiation the subject is seated comfortably on a chair without armrest. When the test starts on AppTUG, a countdown is heard, followed by an auditory and vibratory start cue and when the subject sits back on the chair, the test is over, with the total test time reported. At the end of each trial data is permanently stored on the smartphone in a retrievable database, and uploaded to the "Cloud" for further processing and analysis. This data may also be emailed directly from the device in a comma delimited format (csv), easily accessible by popular spreadsheets.

For each trial, the separate phases of the TUG procedure were segmented in a semi- automatic manner, providing the duration of the stand-up time (SUT) and sit-down time (SDT). SUT is the time elapsed between the subject starting to move his body forwards and the time the subject completes the transfer into the standing up position. Of note that the SUT is data-driven, i.e. it is not measured from the start signal provided by the AppTUG, but rather from the time the subject actually starts moving his body in a forward direction. As reaction time varies between patients, and may reflect not motor, but rather cognitive impairment, we have taken it out of the SUT measurement. The SDT is the time elapsed from the moment the subject finishes walking back to the chair and starts his/her turn in preparation to sitting back down on the chair to the moment the subject's back lies against the backrest of the chair.

Study populations

The study was performed at the Movement Disorders Institute of the Sheba Medical Center and was approved by the local institutional review board. All subjects signed an informed consent form. Participants were either healthy or had a diagnosis of probable normal pressure hydrocephalus (NPH) based on the existence of higher level gait disturbance, and with communicating hydrocephalus per brain imaging which is not explained by another neurological disorder such as parkinsonism, cerebellar ataxia or Parkinson's disease (PD) based on the UK Brain Bank criteria (11). All participants were at least 50-year-old and had no additional problems (including orthopedic or neurological) that could affect their gait and posture. PD patients were assessed after intake of their anti-parkinsonian medications. NPH patients were assessed before lumbar puncture was performed. Data was recorded from 25 HC subjects (age: 69.3±4.6 year-old), 25 NPH subjects (age:72.8±4.7 year-old) and 15 PD subjects (age:68.7±4.1 year-old).

Study procedure

All participants underwent a single assessment in the Movement Disorders Institute, consisting of a 3-meter and a 10-meter TUG, two trials each (interrupted by a 10-second interval), with AppTUG-equipped iPhone attached to their sternum by means of an adjustable elastic strap that was fixed with Velcro. TUG completion times were recorded by using a stopwatch by the various neurologists at the clinic (SIK, SB, SHB and GY, VL, TFK), in parallel to AppTUG. The tests were conducted in a controlled environment, without any obstacles or distractions. The stopwatch started when the AppTUG buzzer turned on and stopped when the subject sat back on the chair. Subjects were wearing their own comfortable shoes, and were instructed to walk at their normal walking speed. If a subject failed to perform the procedure adequately (e.g. due to poor understanding of the task or distraction) that trial was dismissed and repeated. At the end of each trial the data was uploaded to a server and analyzed by Montfort's proprietary algorithms.

Statistical analysis

In order to assess AppTUG measurement accuracy, we calculated the Pearson product moment correlation coefficient (r) between AppTUG completion time and the stopwatch time as recorded by the supervisor. In order to compare between the three subject populations (NPH, PD, HC), single factor ANOVA was performed. P-value < 0.05 was defined as statistically significant.

Results

The mean age ± SD of each group was 69.3 ± 4.6 years for the HC group (n = 25) 72.8 ± 4.7 years for the NPH group (n = 25) and 68.7 ± 4.1 years for the PD group (n = 15). Demographics are shown in the table. Initially, AppTUG accuracy was tested by measuring TUG test completion time for the 25 NPH patients and 25 HC subjects, one 3-meter and one 10-meter trial per subject thus giving a total of 50 samples for each group. High correlation was found (r=0.982) between AppTUG-derived completion time and the stopwatch-derived completion time, as presented in Figure 2 (left). In the case of the 25 HC individuals, an even higher correlation was found (r=0.99), as can be seen in Figure 2 (right). While the HC subjects were recorded by one examiner, the NPH subjects were recorded by six different examiners. If we analyze the NPH samples taken by one examiner, we obtain a similar correlation to that obtained by the single examiner of the HC (r > 0.99 for each examiner).

Groups	N	N males (%)	Mean age (y)	TUG completion time (sec)	Standing up time (sec)	Sitting down time (sec)
NPH	15	8 (53)	69.8 ± 3.4	21.3 ± 5.1*	3.9 ± 1.8*	4.7 ± 2.4*
PD	15	8 (53)	69.3 ± 4.4	19.5 ± 5.9*	2.2 ± 0.6	3.2 ± 1.8**
HC	15	8 (53)	68.7 ± 4.1	12.4 ± 2.3	1.8 ± 0.2	2.5 ± 0.4

Table: *Demographics and iTUG measurements of the participants in the different iTUG evaluations.*

Abbreviations: N: Number of Subjects; y: years; HY: Hoehn and Yahr; sec: Seconds; N.A.: Not Applicable; iTUG: Instrumental Timed Up and Go; HC: Healthy Controls; NPH: Normal Pressure Hydrocephalus; PD: Parkinson's Disease

**p < 0.01*

***p < 0.05*

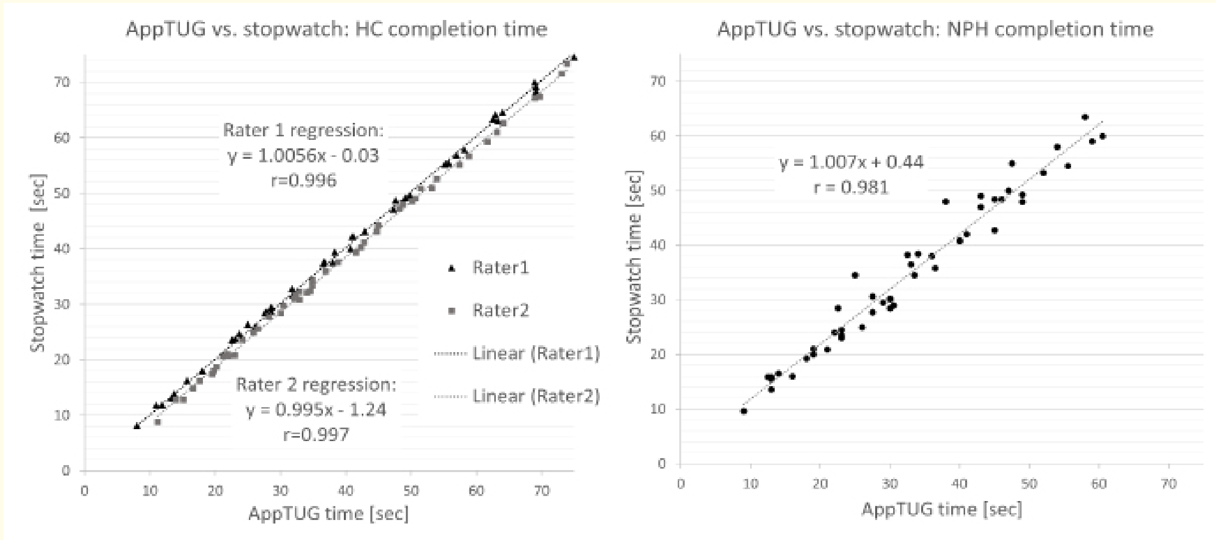

Figure 2: *AppTUG measured time (X axis) and the time measured by an examiner using a stopwatch (Y axis) on NPH (left) and HC (right) subjects. Each graph consists of 50 results from the 25 NPH (left) and HC (right) subjects, one from the 3-meter and one from the 10-meter TUG for each subject.*

We used data obtained from AppTUG for comparing TUG completion time between 15 subjects in NPH, PD, and HC, as presented in figure 3 (left). While NPH average completion time was higher than that of PD, the difference between PD and NPH patients was not significant. NPH and PD had both a longer AppTUG-derived completion time than the HC AppTUG-derived completion time ($p < 0.001$).

On analysis of the phases of the TUG task, the NPH group presented a significantly longer SUT in comparison to both PD and HC groups ($p < 0.001$), as seen in figure 3 (middle subplot). PD SUT is somewhat longer than the HC SUT, but the difference was not significant ($p = 0.06$). The NPH patients also had a significantly longer SDT in comparison to the PD patients ($p < 0.001$), and PD had a significantly longer SDT than for the HC ($p = 0.02$), as seen in figure 3 (right).

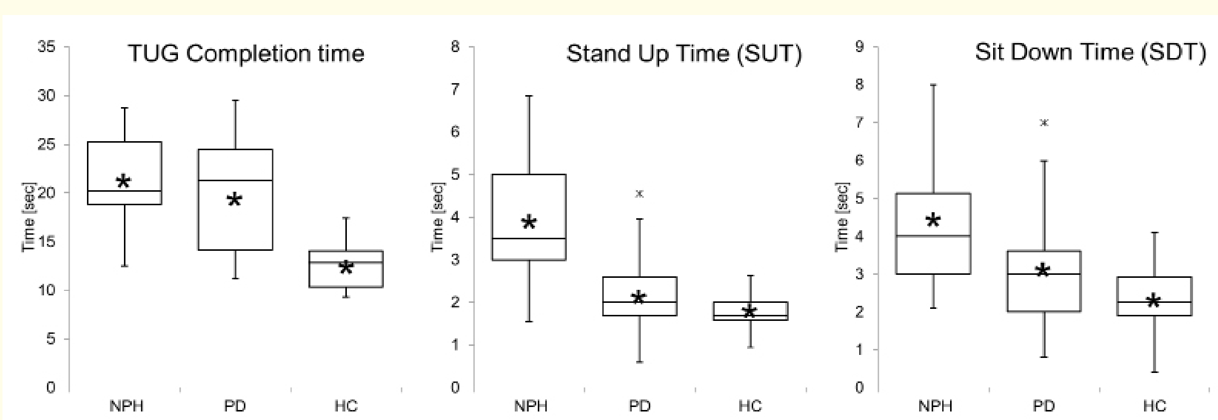

Figure 3: *TUG completion time (left) as recorded by AppTUG for a 3-meter TUG. Comparison between the NPH, PD and control groups. SUT as recorded by AppTUG (middle). Comparison between the NPH, PD and control groups. SDT as recorded by AppTUG (right). Comparison between the NPH, PD and control groups. The mean is noted by asterix and the median by a transverse line within the plotbox.*

Discussion

While previous work has demonstrated that smartphones can be used for measuring TUG in general, our work was focusing on enabling smartphone-based instrumental TUG for practical use in the clinic, and yielding clinically validated results. AppTUG includes all the requirements for the application to be usable in the clinic – not only the recording of the movement, but also, control of the flow of the TUG task and consecutive trials, high quality of recorded data and feasibility of extracting the phases of the task. Furthermore, the AppTUG allows the analysis of multiple features in all 6 dimensions of motion.

We have demonstrated that AppTUG can be used to accurately and automatically measure TUG completion time. This was validated on a group of HC subjects and a group of NPH patients at both 3-meters and 10-meters. When using a stopwatch, measurement error is usually estimated to about 200 milliseconds, for both time points (start and stop time). This measurement error may be specific to each examiner (i.e. user-dependent bias). Furthermore, some physicians stop the measurement before the subject leans against the backrest while others stop it after the patient is fully seated, and some patients sit back in the chair without resting their back on the back of the chair. This lack of standardization is likely to be responsible for most of the inter-examiner variability. These factors, together with some distractions which exist in the clinic, reduce the accuracy of TUG completion time when manually using a stopwatch. AppTUG allows the automatization of nearly the entire procedure, eliminating both start and stop times variability, and generating a standard for identifying when the patient is properly sitting down. Whenever uncertainty occurs, offline viewing of the results can pinpoint the exact timestamp for each event. We therefore believe that AppTUG is more accurate than the manual use of a stopwatch. AppTUG automation also allows running TUG remotely and independently in the patient's natural environment without the need for an examiner or operator.

Having proven AppTUG completion time accuracy, we have compared TUG completion time (as reported by AppTUG) between NPH, PD and HC subjects. As figure 3 shows, there is relatively small and insignificant difference between the NPH and PD populations in TUG completion time, but there is a significant difference between both these groups and the HC group. On analysis of the SUT, NPH subjects were shown to be slower in standing up than both PD and HC, and that PD patients' SUT was similar to that of the HC. SDT seems to offer better separation between the three groups (i.e. NPH, PD, HC) providing statistically significant difference, as can be seen in figure 3. On a broader scale, these findings demonstrate the advantage of TUG segmentation which AppTUG easily provides, over the single measurement of the TUG completion time. AppTUG turns a standard smartphone into a compact, accessible and user friendly tool that can be used either in the clinic or in the patient's home for evaluating gait and balance.

Conclusion

In conclusion, this study demonstrates the usability and validity of using AppTUG to measure TUG completion time, as well as the phases of the TUG task such as SUT and SDT. Walking and turning will be analyzed in future report. Other parameters are extracted from the AppTUG recordings, such as sway, step count, variability of steps etc. Inclusion of these parameters are likely to provide objective measurements of posture and gait function for the diagnosis, prognosis and follow up of neurological disorders in the clinic and for research purposes.

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