A Smartphone Application Suite for Assessing Mobility

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Abstract—**Modern smartphones integrate a growing number of inertial and environmental sensors that can enable the development of new mobile health applications. In this paper we introduce a suite of smartphone applications for assessing mobility in elderly population. The suite currently includes applications that automate and quantify the following standardized medical tests for assessing mobility: Timed-Up-and-Go (TUG), 30 Seconds Chair Stand Test (30SCS), and a 4-stage Balance Test (4SBT). For each smartphone application we describe its functionality and a list of parameters extracted by processing signals from smartphone's inertial sensors. The paper shows the results from studies conducted on geriatric patients for TUG tests and from studies conducted in the laboratory on healthy subjects for 30SCS and 4SBT tests.**

I. Introduction

The rapid proliferation of smartphones and continual growth in smartphone capabilities have opened up new opportunities for health monitoring applications. Modern smartphones include a number of built-in inertial and environment sensors that can be utilized in health and fitness monitoring applications. Modern smartphones typically include accelerometers, gyroscopes, magnetometers, barometers, and humidity sensors. With a growing data processing and communication capabilities, smartphones enable the development of new innovative mobile health applications [1]–[3]. Monitoring type and level of physical activity in elderly is one of the promising mHealth application domains.

The quality of life of elderly is highly correlated with their mobility. Falls are the third leading cause of worldwide chronic disability and approximately 81-98% of hip fractures caused by falls in elderly [4]. Falls not only create serious threat to health among elderly, but the treatment cost and resources also exert heavy economic burden on the society. The risks of falling and of fall related injuries increase with the person's age because of loss of agility, vision loss, and medication side-effects [5].

In this paper we introduce a suit of smartphone applications for mobility assessment. The suite includes applications for automating and quantifying standard mobility tests recommended by the Centers for Disease Control and Prevention (CDC): Timed Up and Go (TUG) [6], 30-Second Chair Stand (30SCS) [7], and 4-Stage Balance test (4SBT) [8]. The applications record and process the signals from the smartphone's gyroscope and accelerometer sensors to extract the parameters that quantify individual phases of the tests. The applications offer an affordable solution for quantifying mobility of elderly with an immediate feedback and automated logging. They can benefit both healthcare professionals and individual users interested in assessing mobility, evaluation of therapeutic interventions, or progression of disease.

Section II describes system architecture of the mobility assessment framework and parameters extracted for each smartphone application. Section III describes signal processing to extract the parameters. Section IV describes the results from preliminary tests performed on the geriatric as well as healthy individuals. Section V concludes the paper.

II. mHealth Applications For Mobility Assessment

Figure 1 illustrates a system architecture of the application suite. The system requires an Android smartphone with built-in accelerometer, gyroscope and orientation sensors. During tests the smartphone is mounted on the subject's chest or back using an elastic band to keep it stationary. Smartphone applications record and process signals from the sensors, extract parameters, and display results on the screen. The applications stop monitoring automatically after the completion of the test. They create test descriptors that include data and time when the tests are taken and all parameters that quantify the tests. The test descriptors are stored in the .csv file on the smartphone and can optionally be uploaded to an mHealth sever via Internet for long-term storage and analysis [9].

The tests can be administered by the subject herself or a nurse can help to set up the tests and provide instructions. The tests can be taken many times a day. Analysis of the parameters collected over longer periods of time may help in tracking long-term changes in mobility and diagnosis of balance impairments. The applications have been tested on Nexus 4, HTC M7 and M8, Motorola RAZR M, and RAZR HD smartphones. The following subsections describe the smartphone applications.

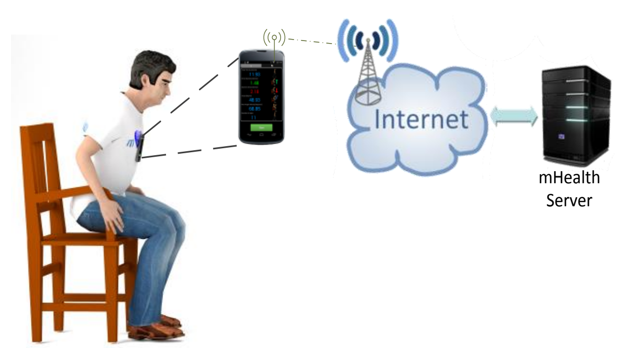

Figure 1. System architecture of mHealth suite for mobility assessment

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A. *Smart Timed-Up-And-Go (sTUG)*

The sTUG application automates and quantifies a widely used Timed-up-and-go (TUG) test [10]. The application quantifies all the phases of the TUG test and produces a list of parameters shown in Table I. In this test, a subject sits in a standard arm chair. The subject uses regular footwear and he/she can use a walking aid if needed. On the command ‘Go’ the subject stands up from the chair and walks to a 3-meter marker on the floor at normal pace, turn around, walk back to the chair at normal pace and sits down on the chair again. Longer TUG times indicate reduced mobility. An older adult who takes more than 12 seconds to complete the TUG test is at high risk for falling [6]. In addition, the health care professionals also observe the subject’s postural stability, gait, stride length, and sway to fill in a form identifying slow, tentative pace, loss of balance, short strides, little or no arm swing, shuffling, or improper use of walking aids.

The sTUG user interface is shown in the Figure 4 (left). The application starts analysis from the moment of detection of a sit-to-stand transition, and stops automatically after detection of a stand-to-sit transition. Important parameters are calculated and displayed instantly on the screen. The raw sensor signals and processed parameters are saved on the phone and sent to the mHealth server.

TABLE I. PARAMETERS FOR TUG CHARACTERIZATION

Param.	Description	Units
d.TUG	Duration of the TUG test	seconds
d.S2ST	Duration of the sit-to-stand transition	seconds
d.LF	Duration of the lean forward phase	seconds
d.LT	Duration of the lift up phase	seconds
d.WALK	Total time of walk	seconds
d.ST2S	Duration of the stand-to-sit transition	seconds
d.PS	Duration of the prepare-to-sit phase	seconds
d.SD	Duration of the sit-down phase	seconds
a.S2ST	Maximum change of trunk angle during d.LF	degrees
v.LF	Maximum angular velocity during d.LF	degrees/s
v.LT	Maximum angular velocity during d.LT	degrees/s
n.STEP	Total number of steps during walking phase	steps
n.SBT	Total number of steps before turn	steps

B. *30 Seconds Chair Stand Test*

The 30SCS test measures the number of stands a person can perform during a 30 second interval which is based on the five-times-sit-to-stand test. The primary goal of this test is to measure the lower extremity strength and endurance, but it can also indicate speed, balance, and mobility of users [11], [12].

The test is conducted using a straight back chair without arm rests and a stopwatch. The subject is sitting in the middle of the chair with feet flat on the floor with hands placed on the opposite shoulders and crossed at the wrists. The typical phases of 30SCS using smartphone on the chest are shown in the Figure 2. On the command ‘Start’ the subject rises to a full standing position and then sits back down holding arms against his/her chest. The subject keeps repeating these steps for 30 seconds. The outcome of the test is the number of times the subject comes to a full standing position in 30 seconds.

The 30SCS application quantifies the 30SCS test by extracting a set of parameters such as duration of sit-to-stand, stand–to-sit, sitting, and standing phases for each cycle of the test [7]. The complete set of parameters for each cycle of the 30SCS test is shown in Table II. The 30SCS smartphone application begins the test when a subject presses ‘Start’ button on the screen. Then the subject makes as many stand-ups as he/she can during 30 seconds; the application makes an acoustic cue (beep sound) after 30 seconds to indicate the test completion. Our application counts the total number of stand-ups as well as total number of complete cycles (stand-up to sit-down). The application displays important parameters immediately on the screen after the completion of the test as shown in Figure 4 (middle). The values of parameters listed along with the raw signals of the test are saved in the .csv file on the smartphone as well as uploaded on the mHealth server for further analysis.

Figure 2. 30 Second Chair-Stand (30SCS) test phases

TABLE II. PARAMETERS FOR 30SCS CHARACTERIZATION

Param	Description	Units
n.SUP	Total number of stand-ups in 30 seconds	number
n.CC	Total number of complete cycles	number
d.CC	Total duration of all complete cycles	seconds
d.CYCLi	Duration of each cycle	seconds
d.S2STi	Duration of the i[th] sit-to-stand transition	seconds
d.LFi	Duration of the lean forward phase	seconds
d.LTi	Duration of the lift up phase	seconds
d.ST2Si	Duration of the stand-to-sit transition	seconds
d.PSi	Duration of the prepare-to-sit phase	seconds
d.SDi	Duration of the sit-down phase	seconds
d.STi	Duration of standing phase	seconds
d.SITi	Duration of sitting phase	seconds
a.S2STi	Maximum change of the trunk in d.LF	degrees
v.LFi	Maximum angular velocity during d.LF	degrees/s
v.LTi	Maximum angular velocity during d.LT	degrees/s

C. *4-Stage Balance Test (4SBT)*

The 4SBT test is used to assess static balance of elderly during four progressively more challenging balancing positions. The subject should not use assistive devices and keep their eyes open. The four respective positions of the 4SBT are shown Figure 3. The positions are described as follows: (a) *Feet together stand* assumes feet are placed side by side; (b) *Semi-tandem stand* assumes that the instep of one foot is touching the big toe of the other foot (c) *Tandem stand assumes* that one foot is placed in front of the other so that the heel of one foot touches the toe of other foot; and (d) *One leg stand* assumes standing on one leg. A nurse supervising the test clearly describes and demonstrates each position and always stands next to the subject to hold his/her arm and help them assume the correct foot position. When the subject is steady the nurse starts measuring time using a stopwatch, but remains ready to catch the subject if balance is lost. If the subject can hold a position for 10 seconds without moving his/her feet or needing support, the test advances to the next position. The test outcomes are times in seconds the subject is able to hold each of four positions. It has been shown that an older adult who cannot hold the tandem stance for at least 10 s is at increased risk of falling [8].

The 4SBT smartphone application consists of four tests that can be selected using the test selector screen. The application starts the test after the user presses ‘Start’ button on the display screen. The 4SBT tests provide the average chest movements during each of the four positions of the balance test. The application uses accelerometer signals to quantify relative displacement of the chest producing parameters described in Table III. The chest displacement values indicate the balance control of the subject. The lower displacement values demonstrate better stability during the tests.

Figure 3. The 4-stage balance test feet positions

TABLE III. PARAMETERS FOR 4 STAGE BALANCE TEST

Param	**Description:** Relative displacement of the chest	Units
s.FTi	Every second in the feet together stand	cm
s.STi	Every second in the semi-tandem stand	cm
s.TSi	Every second in the tandem stand	cm
s.OLi	Every second in the one leg stand	cm

III. SIGNAL PROCESSING

Signal processing in the sTUG application is described in [10]. Raw acceleration and gyroscope data for 3 chair stands during 30SCS test is presented in the Figure 5. From the signal profile, it can be noticed that sit-to-stand and stand-to-sit transition can be divided into separate phases such as leaning forward (characterized by d.LF) and lifting up (d.LT), preparation to sit (d.PS), and sit down (d.SD). We process gyroscope derived angular speeds around the frontal axis for zero crossing, to precisely locate above phases. Additionally, acceleration thresholds are checked to ensure that the leaning forward pattern is caused by an actual motion rather than by swinging forward while still in sitting position. We timestamp all the phases of each cycle for 30SCS and count the number of stand-ups, and the number of complete cycles during the test. We double integrated the 3D vector magnitude of accelerometer signal to quantify relative displacement of the chest during 4SBT test.

IV. RESULTS

We used sTUG for the assessment of mobility of elderly subjects in the Center for Aging, Huntsville, AL. This study was approved by the Institutional Review Board (IRB) of The University of Alabama in Huntsville and all participants provided full written consent. The results of the sTUG for two patients taken during a stability improvement program in the doctor’s clinic are presented in Table IV. The patients went through a mobility improvement program that included a prescribed exercise regimen and management of medication. Three tests were taken in the interval of 3 months during the mobility improvement program. The sTUG test results show that the prescribed regimen helped in the improvement of their overall mobility.

TABLE IV. THE STUG RESULTS RECORDED DURING STABILITY IMPROVEMENT PROGRAM

	Patient#1				**Patient#2**			
Param	Feb	Apr	May	%Change	Feb	Apr	May	%Change
d.TUG	17	15.6	12	-29	15	13	8.4	-44
d.S2ST	1.3	1.1	0.8	-38	1.5	1.4	0.6	-60
d.LF	1.0	0.8	0.6	-40	1.0	1.0	0.3	-70
d.LT	0.4	0.3	0.2	-50	0.5	0.5	0.3	-40
d.WALK	14	13	9.8	-30	11	10	6.9	-37
d.ST2S	1.5	1.5	1.4	-6.6	1.9	1.6	0.9	-53
d.PS	0.3	0.6	0.3	0.	0.8	0.3	0.2	-75
d.SD	1.2	0.9	1.1	-8.3	1.1	1.3	0.7	-36
a.S2ST	54	64	58	7.4	54	59	51	-6
v.LF	176	302	326	85	150	164	273	82
v.LT	-8	-1.2	-10	25	0	0	-17	-
n.STEP	21	22	16	-23.8	21	22	10	-52
n.SBT	10	10	8.0	-20	11	12	5.0	-55

Table V presents the average/standard deviation of the 30SCS cycle parameters for 5 healthy individuals. We estimated slope of the regression line for duration of each cycle (d.CYCL). Slope values greater than one indicate that a subject needs more time to complete the cycle as test progresses. The 95% confidence interval for the coefficient in the regression is also presented.

TABLE V. THE PRELIMINARY 30SCS TEST RESULTS

Param	**P#1**	**P#2**	**P#3**	**P#4**	**P#5**
n.SUP	10	12	11	13	16
n.CC	9	12	10	12	15
d.CC	28.23	29.80	28.71	28.60	28.90
d.S2STi	1.0±0.2	1.0±0.25	0.96±0.2	1.0±0.17	0.7±0.15
d.LFi	0.5±0.2	0.42±0.2	0.3±0.16	0.5±0.15	0.31±0.2
d.LTi	0.6±0.1	0.6±0.04	0.6±0.14	0.6±0.03	0.4±0.02
d.ST2Si	1.2±0.4	1.1±0.17	0.9±0.35	1.4±0.04	0.8±0.22
d.Psi	0.6±0.3	0.5±0.15	0.5±0.23	0.6±0.03	0.41±0.1
d.SDi	0.6±0.2	0.6±0.05	0.5±0.14	0.8±0.03	0.44±0.1
d.STi	0.3±0.5	0.1±0.17	0.4±0.30	0.1±0.06	0.13±0.1
d.SITi	0.5±0.7	0.2±0.03	0.54±0.8	0.4±0.12	0.35±0.1
a.S2STi	41±13	48±22.2	57.9±10	40.3±5.2	29.6±3.0
v.LFi	129±24	172±47	268±19	144±18	192±28
v.LTi	10±13	12.7±19	2.74±8.2	7.59±7.4	31.6±28
d.CYCLi	2.9±1.5	2.5±0.3	2.7±1.09	2.38±0.2	1.9±0.25
Slope CYCL/CI	1.12/ 2.0-2.14	1.09/ 1.9-2.5	1.03/ 2.4-2.58	1.03/ 2.2-2.34	1.05/ 1.8-2.02

Table VI presents the 4SBT results performed on two healthy subjects simulating small movement in the chest in order to balance the respective standing positions. Mean and standard deviation of the displacement values for each position are presented. Higher values of displacements are associated with the decrease in stability.

To verify the correctness of the parameter extraction, we use a custom program that captures videos of the experiments and synchronizes them with measurements. The videos are annotated manually to identify individual transitions and extract time parameters. TABLE VII and TABLE VIII compare the d.TUG and d.S2ST parameters from the sTUG and 30SCS applications, respectively and the corresponding parameters extracted from the videos. The average error is in the range of 0.96±1.65 % for the sTUG parameters and in the range of 2.97±4% for the 30SCS parameters.

TABLE VI. THE PRELIMINARY 4-STAGE BALANCE TEST RESULTS

	Patient#1				Patient#2			
i	s.FT	s.ST	s.TS	s.OL	s.FT	s.ST	s.TS	s.OL
1	1.2	0.5	8	2.1	3.1	2.5	3.4	0.6
2	13.1	0.4	1.2	3.4	5.3	3.1	4.8	3.8
3	5	0.8	0	8.6	0.3	1.8	11.4	1.8
4	5.4	0.9	16.2	1.6	2.4	3.7	3.3	0.6
5	2	0.2	5.6	4.9	2.2	4.5	7.6	0.8
6	1.9	2.2	4.5	3.3	1.5	4.2	0.8	16.4
7	2.1	5.1	4.5	11.3	3.1	2.2	6.5	7.2
8	4.1	3.8	2.3	1.3	2.9	7.6	2.9	23
9	1.6	2.6	1.5	2.2	0.4	1.7	2.4	0.9
10	2.7	7.1	5	8.3	9.2	2.8	2.8	5.8
M± SD	3.9± 3.36	2.36± 2.2	4.48± 4.4	4.7± 3.31	3.04±2 .47	3.41± 1.67	4.59± 2.95	6.09± 7.29

TABLE VII. COMPARISON OF d.TUG: ANNOTATED VIDEO VS sTUG APP

Video	10.38	10.54	9.76	8.57	8.47	8.64	10.2	9.69	9.59
sTUG	10.5	10.5	9.8	8.79	8.61	8.48	10.6	9.84	9.54
% Err	1.16	-0.38	0.41	2.57	1.65	-1.85	3.92	1.55	-0.52

TABLE VIII. COMPARISON OF d.S2ST: ANNOTATED VIDEO VS 30SCS APP

Video	1.69	0.93	1.09	1.05	1.02	1.05	1.08	1.09	1.05
30SCS	1.63	0.9	0.96	1	0.98	1.02	1.01	1.04	1.05
Error [s]	0.06	0.03	0.13	0.05	0.04	0.03	0.07	0.05	0

Figure 4. Smartphone applications screens for sTUG, 30SCS and 4SBT.

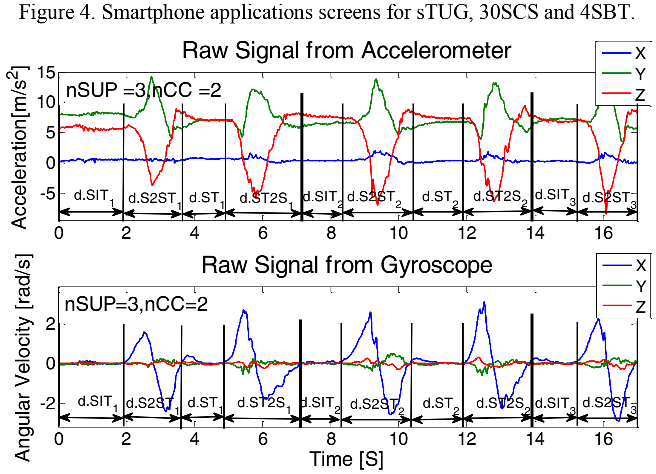

Figure 5. Accelerometer and gyroscope signal variation during 30SCS

V. CONCLUSION

Proliferation of smartphones that integrate a growing number of sophisticated sensors creates a number of opportunities for instrumentation and quantification of standard monitoring and diagnostic procedures. In this paper we describe a suite of smartphone applications that completely automates frequently used mobility assessment tests: TUG, 30SCS, and 4SBT. The applications provide instantaneous feedback to the user and automatically upload the test results on mHealth server. The applications have been tested on a group of healthy volunteers and Parkinson's disease patients and showed promising results. By utilizing commodity smartphones, the application suite offers an affordable tool for instantaneous quantification of the mobility assessment. Analysis of the parameters collected over longer periods of time may help in tracking progression of mobility and balance impairments.

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