Automated Time Up and Go Test with Redundant IMU System

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Abstract. Throughout the years the relevance of Time Up and Go Test (TUG) to qualify or even quantify the patients' global motor state became clear. Nonetheless, it is evidenced that the conventional result, i.e, the total duration of TUG, is not able to describe a specific problem. The aim of this work is to develop a multi-sensor wearable platform based on redundant inertial sensors (RIMU) able to automatically calculate both the user cadence and the duration of each TUG phase. Eight volunteers without gait disabilities wore the RIMU system during 5 meters TUG, and the data were compared to reference systems. The results presented an average RMSE (root-mean-square error) of 5.20 steps/min for cadence and 0.48 seconds for total duration TUG. In conclusion, the proposed instrumented TUG is an easy-to-perform test and may be an alternative to assess the initial motor state of patients.

Keywords*:* Timed Up and Go. Inertial sensor. Gait Analysis. Wearable sensors.

1. INTRODUCTION

World Population Ageing 2017 Highlights (United Nations, 2017) report that currently older people (aged 60 years or over) reaches almost one billion. According to the projections for 2017 (IBGE, 2010), 12.6 percent of total population is elderly in Brazil. This situation demands major changes in public policies, what concerns governments and health specialists. Within possible plans, the training of human resources for geriatric care should be highlighted. Moreover, it has been evidenced that age itself represents a risk factor for cognitive decline and development of motor impairments (Bishop et al., 2010). Falls, immobility and neurodegenerative disorder are the major causes of disability in elderly people. Also, age influences in the clinical progression of diseases, such as Parkinson disease (PD), which is a degenerative disorder that affects the central nervous system (Reeve et al., 2014).

Under this conditions, different protocols and instruments are used to assess functional mobility of people. Gait information has been acknowledged by clinical community, being of great importance in the identification of abnormalities and risk of falls (Wren et al., 2011). Thus, Gait Analysis (GA) is a useful tool to assist diagnosis, find the best therapy and quantitatively provide feedback to clinicians and patients.

The gold standard in motion analysis comprises force platforms, infrared cameras and markers positioned on the body. Although this whole system is highly accurate, it has high cost and requires suitable infrastructure and specialized personnel, which may hinder its use in clinical practice (Muro-De-La-Herran et al., 2014).

In this context, wearable systems, such as inertial measurement units (IMUs), are being widely used because of its light-weight, portability, easy operation and maintenance, and much lower cost. Moreover, IMUs make possible to monitor patients during their daily activities at home, enhancing the use of this technology in the clinical routine, motor rehabilitation and telerehabilitation strategies, making possible to increase the amount of information available to medical specialists, improving diagnoses and therapies.

A typical clinical test used to measure physical function and motor speed in elderly and patients with PD is the Timed Up and Go (TUG). This test consists of measuring, using a manual chronometer, the time that a patient takes to rise from a chair, walk three meters, turn around, walk back and sit down (Podsiadlo and Richardson, 1991). Different approaches using TUG test can assist physiotherapists to define predictors of the risk of fall and severity of motor impairment.

On the other hand, TUG test using IMUs has shown some advantages if compared to stopwatch traditional TUG test, such as estimating automatically additional parameters about the patient performance (Sprint et al., 2015). A recent research done by Beyea et al. (2017) present the validation of TUG test using an IMU fixed to the torso (at approximately the T2-T3 spine level) against motion capture cameras. The authors found high agreement when total TUG time and walk times were estimated for chair activities, but poor for turn times.

Palmerini et al. (2013) used a single accelerometer placed on the lower back of PD patients and healthy control subjects. The authors estimated some parameters at different phases of TUG test, aiming to identify and quantify the motor patterns differences between these subjects. Finally, they concluded that iTUG (instrumented TUG), which include a frequency analysis, is a good tool (misclassification of 22.5%) to discriminate PD motor impairment when compared to only temporal outcome of the traditional TUG test.

In another research (Salarian et al., 2010), seven inertial sensors (3D accelerometers and 2D gyroscopes) were attached to upper and lower limbs of PD and control subjects. The authors claim that instrumenting the TUG provides objective assessment that goes beyond temporal measures. For instance, parameters such as horizontal velocity of trunk and arm-swing angular displacement showed significant difference between the two groups. Thus, this approach provides other relevant quantitative outcomes for testing anyone with balance or gait deficits.

These researches present some disadvantages, limiting the analysis only to temporal parameters when using a single sensor. In the case of the latter research, although the authors presented some angular parameters, the use of a big number of sensors would increase the setup difficulty and costs.

This paper presents a motion capture system, which comprises a single unit able to collect, process and send signals from two IMUs placed on the same board, aiming to improve the general system precision and performance. The hypothesis is that having two different IMUs (from two different vendors) creates the possibility to reduce not only the Gaussian noise, but also errors whose sources are non-linear. In fact, according to Skog et al (2014), the non-linear errors cannot be reduced by using a multi-IMUs platform (MIMU) of the same brand.

Our system is able to get gait speed, cadence and duration of TUG phases, which can help to describe the patient's global motor state when TUG is implemented. Although commercial systems may be found with some similarities, this work is included in a research and development partnership that aims to develop an own motion capture system, with lower cost and accessible to a greater number of Brazilian researchers, rehabilitation professionals and final users.

This paper is organized as follows: Section II presents the experimental setup of the sensor analysis, Section III presents the obtained results, limitations and discussion, and Section IV presents the conclusions and future works.

2. MATERIALS AND METHODS

2.1. Redundant Inertial Measurement Unit (RIMU)

The developed system, shown in Fig. (1), has dimensions of 46x36mm. The embedded microcontroller is a Cortex M0+ (ATSAMC21E18A, Atmel), which is capable of simultaneously communicating through two different TWI (Two Wire Interface) peripherals with the following inertial measurement units: BNO055 (Bosh), LSM6DS33 and LIS3MDLTR (STMicroelectronics). The data collected from these sensors are transferred online to a server using a 2.0 Bluetooth module (HC-05) operating over the SPP protocol that runs a MATLAB script capable of extracting the gait parameters. It is important to mention that the timing of this process is controlled by a M0+ internal timer, so the sampling frequency remains constant throughout the all test, independently of the server's operational system jitter.

The BNO055 is a 9 degrees of freedom (DoF) system on chip (SoC) with 3-axis accelerometer, gyroscope and magnetometer in addition to an embedded Cortex M0 that processes the data from the sensors, executes calibration and fusion algorithms, and generates data. The LSM6DS33 is an integrated circuit (IC) composed of 16 bits 3-axis accelerometer and gyroscope, while the LIS3MDLTR is a 16 bits 3-axis magnetometer. The resulting system has 18 DoF.

The system can operate in two different modes with two different sampling frequencies:

- The first mode is characterized by collecting data from selected sensors (LSM6DS33 and BNO055), which includes fusion (quaternions and linear acceleration without gravity) and non-fusion (raw linear acceleration and angular velocity) data at a sampling rate of 100 Hz, totalizing 38 bytes every 10 ms.
- At the second mode only non-fusioned data are collected from the LSM6DS33 and the LIS3MDLTR at a sampling rate of 500 Hz, totalizing 18 bytes every 2 ms.

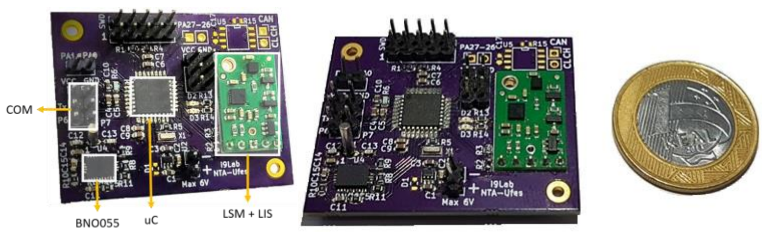


Figure 1. Redundant IMU (RIMU). Motion capture sensor using BNO055, LSM6DS33 and LIS3MDLTR.

2.2. TUG and gait parameters

During a traditional TUG test, a patient must rise from an armchair, walk 3 meters, turn around an object, walk back and sit. Even though many others parameters can be analyzed, the only parameter generally reported in this test is its duration (Podsiadlo and Richardson, 1991), which stunts the addressing of specific motor problems.

Instead, our system is able to evaluate the duration of all TUG phases, which are divided as (Fig. (2)): Rise (RI), Gait 1 (GA1), Turn 1 (TU1), Gait 2 (GA2), Turn 2 (TU2) and Sit (SI). Also, our system uses a 5 m walkway, instead of the traditional 3 m of length. Thus, our system allows the patient to develop a more complete and periodic gait pattern, such as reported by (Palmerini et al., 2013; Salarian et al., 2010). Additional parameters, such as gait speed and cadence, can be also recorded and evaluated. Cadence is understood as the number of steps per time unit, generally minutes, and gait speed is the distance traveled by the full body in a time period (Whittle, 2007). In summarize, the following parameters can be assessed by our system:

- Gait average speed (m/s)
- Cadence (step/min)
- Duration of rise (RI) phase (s)
- Duration of Gait (GA) phase (s)
- Duration of Turn (TU) phase (s)
- Duration of Sit (SI) phase (s)

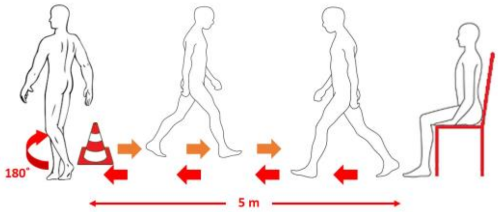


Figure 2. TUG phases: Rise (RI), Gait 1 (GA1), Turn (TU), Gait 2 (GA2) and Sit (SI).

2.3. Experimental Setup

Our RIMU was placed on the lower trunk (lumbar spine) at L4-L5 intervertebral segment. The RIMU describes a local coordinate system defined as y-axis pointing cranially and z-axis pointing posteriorly and x-axis orthogonal to the other two, towards the right. TUG analysis was performed using the first mode operation mentioned in Section 2.1 (sample rate of 100 Hz), with data acquired through MATLAB.

A Tech MCS IMU-based commercial system (Technaid, Spain) was used as a reference to estimate the times of heel strike (HS) and toe off (TO) gait events used to identify the quantity of steps. The system comprises a HUB, which collects, synchronizes and sends the signals to a laptop and two Tech-IMUs, which were positioned on left and right foot. Each Tech-IMU integrates an accelerometer, a gyroscope and a magnetometer, each one of three-dimensions. Only the gyroscope was used to detect HS and TO events. Data were acquired using Tech MCS Studio software with a sampling frequency of 50 Hz. A synchronization signal was generated from Tech MCS HUB to RIMU, in order to warrant data comparison at the same time instant.

A digital chronometer with lap option was used to measure the time of each TUG phase, such as aforementioned. Floor markers were used to indicate distance of 50 and 70 cm, in order to allow the volunteers to adopt a comfortable step length according to their height for later comparison. Also, these markers allow having a reference of the number of step performed during the test. In addition, a cone was placed at the end of the walkway to mark the turning point.

2.4. Data processing

To identify motion characteristics, a single test was performed with intervals of approximately 10 s between different TUG phases, to allow identifying and selecting the signals that presented the best motion patterns according to each phase. Once the signals of interest were selected, the average of the readings of the two sensors (Bosch and STMicroelectronics) signal was first realized, then a zero-phase Butterworth low-pass filter with a cut off frequency of 10 Hz was applied.

<u>Rise and Sit detection</u>: Angular velocity was used to estimate motion from sit to stand. Medial-lateral (ML) axis of motion, which correspond to RIMU gyroscopes x-axis was analyzed too. To identify the RI phase, a pattern was identified at the beginning of the signal, which presents first a negative peak (indicating the inclination of the user to push and leaving the chair – seat off) and a second positive peak (when the user reaches the upright position). To identify the initial instant of RI, a variance analysis to estimate the start of the movement was performed.

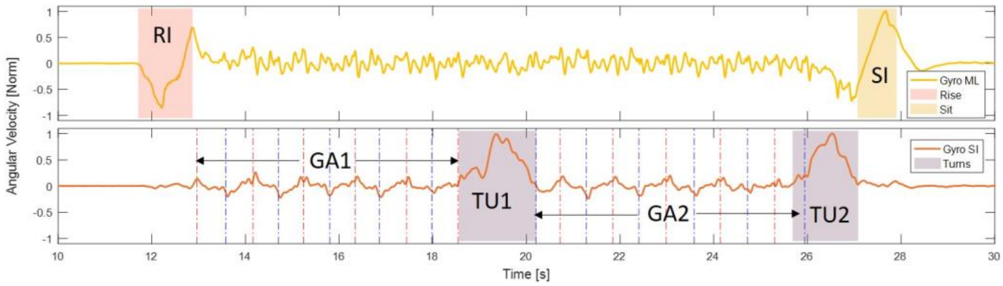
For sit detection, the same axis of movement was analyzed. Two peaks were also identified. The first peak is negative (indicating inclination of the user to sit-down and reach the chair) and the second peak is positive (which corresponds to user movement to reach straight posture and lean on the back of the chair).

<u>Turns detection</u>: Angular velocity around superior-inferior axis of motion was used to estimate turns. This axis corresponds to the RIMU gyroscopes y-axis. A moving average window and a threshold were applied to find the time where the turns occurred. An algorithm was implemented to detect if the turn was clockwise or counterclockwise.

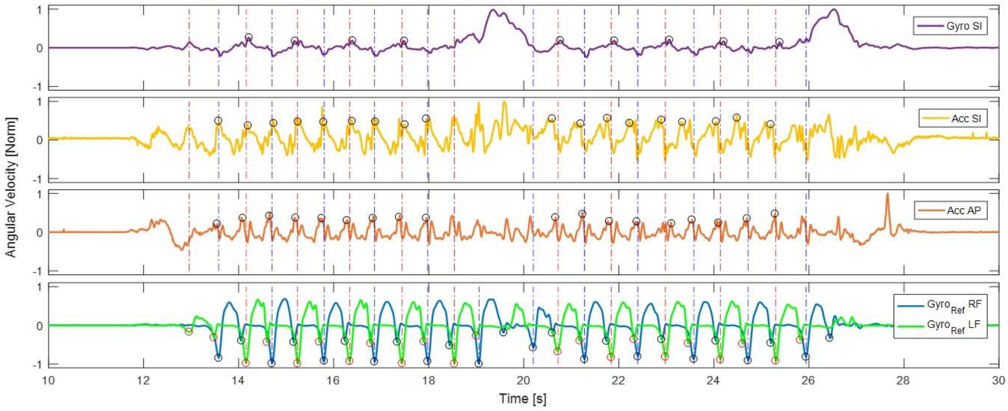
Motion patterns of RI, TU and SI phases are shown in Fig. (3a).

<u>Gait Speed and Cadence estimation</u>: Linear accelerations and angular velocity were used to estimate gait speed and cadence. Superior-inferior (SI) and anterior-posterior (AP) axes of motion were analyzed (corresponding to y-axis and z-axes of the accelerometers and y-axis of the gyroscopes). Then, positive peaks that represent steps (acceleration signal) or stride (angular velocity signal) were detected. Later, the time between each peak was calculated in order to estimate the cadence corresponding to each signal. From each resulting vector, the highest and the lowest cadence values were discarded, and the final cadence was found through an average of the remaining values.

Also, the duration of gait was used to calculate the gait speed during 5 m walkway. Figure (3b) shows the detected peaks to estimate cadence.



(a)



(b)

Figure 3. Motion patterns of the user # 2. (a) Angular velocity around medial-lateral (Gyro ML, yellow line) and superior-inferior (Gyro SI, orange line) axes were used to identify Rise, Sit and Turns (red, yellow and purple shadows, respectively). (b) Angular velocity of right foot ($Gyro_{Ref}$ RF) and left foot ($Gyro_{Ref}$ LF) were used as reference to identify steps. Angular velocity (Gyro SI, purple curve) and accelerations (Acc SI and Acc AP, yellow and orange lines) around superior-inferior and anterior-posterior axes were used to estimate cadence and gait speed. Red and blue dashed lines indicate TO events of the left and right feet, respectively. Black circles (in Gyro SI, Acc SI and Acc AP curves) indicate TO events of right or left foot in accordance with the reference sensors.

2.5. Experimental protocol

Eight volunteers without gait disabilities (5 men and 3 women, 28.1 ± 5 years old, average height 1.73 ± 0.10 m) were involved in this experiment. All sensors (one RIMU and two Tech-IMUs) were placed as described in section 2.3. The volunteers were asked to sit and remain at upright posture for approximately 10 s, then perform TUG phases (RI, GA1, TU1, GA2, TU2 and SI) using selected shoes along a 5 m pathway at comfortable speed. Each subject performed five trials. The duration of each TUG phase was registered using a digital chronometer. All subjects gave informed consent to participate in the study, which was authorized and approved by the Ethical Committee of UFES (CAAE: 64801316.5.0000.5542/2017).

3. RESULTS AND DISCUSSION

As a representative case, the motion patterns of one trial of user # 2 to identify the TUG phases and cadence are shown in Fig. (3). The algorithm described in section 2.4 was applied to each trial. Data from two trials out of forty trials were corrupted: for one case the reference system did not work properly and, for the other the RIMU, the sensor lost data. Therefore, one trial of each volunteer was randomly discarded. Mean and standard deviation of each parameter are presented in Table 1.

The discrimination between the RI and GA1, GA2 and TU2, TU2 and SI was clear, such as shown in Fig. (3). However, the identification of the beginning and ending of TU1 was difficult for tall volunteers. Such aspect can be related to higher levels of trunk movements around the Superior-Inferior axis. To correct this problem, a two-state turn detection algorithm was latter implemented and applied, which consists of a second peak search with variable threshold that is a function of peak magnitude, TU1 duration and signal variance.

In future analysis, additional parameters such as patient height and leg length will be considered to the algorithm improve the TU1 quantification.

Table 1: Mean and standard deviation (STD) of the automatic RIMU parameter extraction.

Vol.	Duration [s] Mean (STD)							Cad. RIMU [steps/min]		Speed RIMU [m/s]		Cad. Technaid [steps/min]		RMSE Cad. [steps/min]	
	RI	GA1	TU1	GA2	TU2	SI	Total	GA1	GA2	GA1	GA2	GA1	GA2	GA1	GA2
1	1.34	5.00	2.07	3.65	1.42	0.80	14.28	103.82	105.28	1.00	1.38	107.30	107.60	4.57	5.89
	(0.08)	(0.18)	(0.19)	(0.44)	(0.14)	(0.20)	(0.57)	(1.52)	(9.99)	(0.04)	(0.17)	(2.40)	(4.53)		
2	1.35	6.97	1.99	5.73	1.47	0.81	18.32	100.49	101.65	0.72	0.88	95.91	94.29	7.92	12.91
	(0.16)	(0.42)	(0.02)	(0.36)	(0.05)	(0.19)	(0.75)	(5.57)	(7.76)	(0.05)	(0.06)	(4.42)	(5.69)		
3	1.32	4.82	1.76	4.39	1.93	1.25	15.47	94.01	96.09	1.04	1.14	93.85	95.54	4.09	2.84
	(0.10)	(0.42)	(0.28)	(0.27)	(0.10)	(0.14)	(0.39)	(4.92)	(5.84)	(0.10)	(0.07)	(1.22)	(2.90)		
4	1.50	5.61	1.82	4.86	2.01	1.98	17.79	99.64	94.37	0.89	1.03	98.36	97.97	7.18	6.91
	(0.25)	(0.28)	(0.28)	(0.27)	(0.21)	(0.09)	(0.58)	(2.64)	(6.42)	(0.04)	(0.06)	(7.24)	(12.92)		
5	1.29	5.56	1.73	5.84	1.46	1.81	17.70	105.36	102.74	0.90	0.86	101.01	100.59	4.13	3.78
	(0.40)	(0.31)	(0.28)	(0.30)	(0.19)	(0.69)	(0.93)	(4.37)	(3.04)	(0.05)	(0.04)	(3.51)	(3.98)		
6	1.51	5.23	1.24	4.10	1.57	0.44	14.08	98.11	99.23	0.96	1.22	96.65	95.65	3.69	4.70
	(0.21)	(0.52)	(0.01)	(0.15)	(0.12)	(0.29)	(1.25)	(1.31)	(5.10)	(0.09)	(0.05)	(4.93)	(1.62)		
7	1.29	6.10	1.68	5.61	1.61	0.56	16.85	106.70	110.23	0.82	0.89	108.81	108.12	2.28	6.21
	(0.14)	(0.49)	(0.27)	(0.21)	(0.15)	(0.05)	(0.67)	(4.58)	(4.27)	(0.07)	(0.03)	(4.35)	(4.42)		
8	1.26	4.73	1.42	3.75	1.09	0.65	12.91	102.10	99.83	1.06	1.33	99.57	101.09	4.42	1.71
	(0.21)	(0.24)	(0.33)	(0.17)	(0.14)	(0.30)	(0.31)	(5.14)	(1.42)	(0.05)	(0.06)	(0.99)	(2.61)		
Mean	1.36	5.50	1.72	4.74	1.57	1.04	15.92	101.28	101.18	0.93	1.09	100.18	100.11	4.78	5.62
	(0.09)	(0.75)	(0.27)	(0.90)	(0.29)	(0.58)	(2.02)	(4.13)	(5.06)	(0.12)	(0.21)	(5.35)	(5.35)		

Table 2 shows the duration of the TUG phases timed using a digital chronometer. During the execution of TUG tests it was clear that manually-measured time of each internal TUG phase is not a reliable task to untrained researchers. Such conclusion is evidenced by slightly higher standard deviations of internal phases when manually timed if compared to the RIMU system. The average total duration of TUG test calculated by the RIMU system was 15.92 (2.02) s, while by the manual procedure was 15.54 (2.04) s. Cadence presented an average (for all subjects) of the root mean square error (RMSE) of 5.20 step/min and a RMSE of 0.48 s for total duration of TUG, which represent less than 5 % of error.

Another relevant aspect is the smaller gait speed found during this test compared to other reports in literature, such as pointed out by Steffen et al (2002). This aspect is probably related to two factors: the first one is the inclusion of acceleration and deceleration cycles in the average gait speed calculations, and the second is the limitation of the step length in only two possible lengths, which demands more attention of the user, implicating a harder task, if compared to natural gait.

Table 2: Mean and standard deviation (STD) of manually-measured times of TUG phases.

Vol.	Duration [s]						Total RMSE time [s]
	RI	GA1	TU1	GA2	TU2+SI	Total	
1	0.97	4.41	1.85	4.03	2.12	13.38	0.47
	(0.23)	(0.31)	(0.25)	(0.37)	(0.44)	(0.46)	
2	1.22	6.19	1.53	6.76	1.79	17.49	0.76
	(0.35)	(0.52)	(0.22)	(0.53)	(0.73)	(1.04)	
3	1.05	4.81	1.87	4.62	3.33	15.67	0.33
	(0.49)	(0.11)	(0.17)	(0.31)	(0.28)	(0.78)	
4	1.59	5.03	2.16	4.94	4.19	17.91	0.60
	(0.33)	(0.23)	(0.16)	(0.63)	(0.92)	(0.77)	
5	0.93	6.09	1.69	5.87	2.11	16.91	0.65
	(0.28)	(0.15)	(0.21)	(0.34)	(0.40)	(0.90)	
6	1.09	4.78	1.34	4.49	2.03	13.72	0.44
	(0.40)	(0.81)	(0.43)	(0.31)	(0.53)	(1.37)	
7	0.93	5.85	1.72	5.64	2.52	16.64	0.31
	(0.14)	(0.29)	(0.23)	(0.35)	(0.12)	(0.54)	
8	1.00	4.44	1.51	3.98	1.65	12.58	0.29
	(0.16)	(0.13)	(0.13)	(0.05)	(0.03)	(0.13)	
Mean	1.10	5.20	1.71	5.04	2.47	15.54	0.48
	(0.22)	(0.73)	(0.26)	(0.97)	(0.87)	(2.04)	

4. CONCLUSIONS AND FUTURE WORK

This work presents the development of a wearable and viable system to perform TUG test automatically. The signals that have the best correlations with each TUG event were identified and presented. The proposed algorithm was able to identify, without major failures, cadence, gait speed and duration of TUG phases executed by eight different volunteers of both genders, with different heights, weights and ages. Such good results are attributed to the quality of the acquired signal and the adaptive features of the presented algorithm, which uses thresholds that are function of signal variance and peak magnitude, characteristics that highlights the robustness of the proposed system.

Further validation to compare the RIMU performance against gold reference motion capture systems and the execution of TUG test with elderly or with motor issue patients will be addressed in the future.

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6. RESPONSIBILITY FOR INFORMATION

The authors are solely responsible for the information included in this work.