# Use of Wearable Inertial Sensor in the Assessment of Timed-Up-and-Go Test: Influence of Device Placement on Temporal Variable Estimation

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**Abstract.** The "Timed Up and Go" (TUG) test is widely used in various disorders to evaluate subject's mobility, usually evaluating only time execution. TUG test specificity could be improved by using instrumented assessment based on inertial sensors. Position of the sensor is critical. This study aimed to assess the reliability and validity of an inertial sensor placed in three different positions to correctly segment the different phases in the TUG test. Finding demonstrated good reliability of the proposed methodology compared to the gold standard motion analysis approach based on surface markers and an optoelectronic system. Placing the sensor just beneath the lumbar-sacral joint reported the lower values of deviation with respect to the gold standard. Optimized position can extend the proposed methodology from the clinical context towards ubiquitous solutions in an ecological approach.

**Keywords:** Inertial sensor · Sensor position · Timed-Up and Go test · Optoelectronic system · Phases durations

## 1 Introduction

The "Timed Up and Go" (TUG) test is one of the most widely used criteria to assess subject's mobility and balance. TUG test is specifically composed of several distinct subtasks that aim to mimic in a clinical context several elements of normal daily life


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activities. In particular, TUG test requires that the subject is observed and timed while he/she rises from a chair, walks for a defined distance (usually short range, such as 3 meters), turns, walks back, turns and sits down again [1]. TUG test was reported to have good correlation with subject's performance in activities of daily living, gait speed and static and dynamic balance abilities, and patient's capacity to safely walk around [2]. TUG test is, for instance, classified as "recommended" for the assessment of gait and balance in Parkinson's disease (PD) [3] and plays a fundamental role in the prediction of falls in frail older patients [4] and post-stroke subjects [5], it can be used to assess also musculoskeletal disease, such as spine impairments and degenerative conditions [6, 7] and hip fracture [8]. In TUG test temporal information about subtasks duration and transitions are fundamental to assess subject's cognitive and motor performance and define precise constraints able to support clinicians in the diagnosis of specific diseases [9, 10].

The necessity to increase the specificity and sensitivity of the test for the quantification of age-related performance in mobility, balance and overall function - led to the introduction of instrumented assessment [11–17]. In particular, wearable and mobile technologies have been providing optimal configurations and good results in the assessment of balancing [18], elderly frailty [19], fall risk [20–22], in the classification of PD patients [23] and early-stage multiple sclerosis [24] detection of freezing of gait (FOG) [17] - providing feedbacks to both subjects and clinicians [16, 25–27], in the evaluation of cognitive impairments including day-long acquisitions [13] and their relationship with motor function [28] and ageing [29]. Furthermore, instrumented TUG can provide also information about the kinematics of the functional tasks, including accelerations, and angular velocities [30, 31]. However, there are several issues, scientific literature only partially dealt with. Timing and transitions between different phases could in fact drive important clinical information from both diagnostic and prognostic point of view [9]. Correct estimation of times are therefore fundamental.

Following the state-of-the-art and scientific literature, we hypothesized to be able to correctly estimate the TUG phases in terms of temporal information by using a single inertial sensor placed on the lower back of the subject. In this perspective, it was worth to analyze how the placement of this sensor could specifically influence the estimation of TUG timing and phases. Therefore, the main objective of this study was to evaluate the reliability and validity of using acceleration and angular velocity data during the performance assessment associated in a TUG test, with respect to a gait analysis system used as "gold standard".

## 2 Materials and Methods

### 2.1 Study Design and Subjects Selection

An observational transversal analytical study with repeated measurements was designed to test intra-subject variability and validity of the proposed method with respect to the gold standard. Exclusion criteria were the presence of musculoskeletal disorders, any malignancy, pain or prior surgeries to limbs and spine.

### 2.2 Instrumentations

G-Sensor device (BTS Bioengineering, Italy) was the inertial sensor used in this study. This module integrated 4 triaxial accelerometer (16 bit/axes with multiple sensitivity ±2, ±4, ±8, ±16 g), 4 triaxial magnetometer (13 bit, ±1200 uT), 4 triaxial gyroscope (16 bit/axes, with multiple sensitivity ±250, ±500, ±1000, ±2000 °/s) and a GPS receiver (with a position accuracy of 2.5 m up to 5 Hz, or 3.0 m up to 10 Hz), within a volume of 70.0 × 40.0 × 18.0 mm. The inertial unit could thus provide both accelerations and angular rates (up to 200 fps). The sensors fusion technology could provide also information about sensor orientation and position. For the acquisitions performed in this study accelerometer range was set to ±2 g, gyroscope range to ±2000 °/s, acquisition frequency to 100 Hz. Connectivity to laptop for acquisition was ensured via Bluetooth 3.0 (class 1.5, range up to 60 m LOS). In order to set the gold standard reference, an 8-cameras optoelectronic motion analysis system (Smart DX, BTS Bioengineering, Italy) with passive retroreflective spherical surface markers (15 mm diameter) was used to acquire kinematic data (100 fps). Specifically designed markers protocol is hereinafter reported, whereas a specific kinematic model was develop to allow for correct tracking and parameters identification. After the proper procedure, a calibrated area of about 4000 × 3000 × 3000 mm, with an error on marker position identification <1 mm, was obtained.

### 2.3 Acquisition Protocol

The participants wore the inertial sensor attached in a semi-elastic neoprene belt on the lower back. Three different placement of the inertial sensor were used. In particular, the device was placed [**POS 1**] just over the iliac alae (i.e. above the iliac crests), [**POS 2**] just beneath the lumbar-sacral joint (i.e. under the line connecting the two posterior superior iliac spines - PSIS) and [**POS 3**] just over the lumbar-sacral joint. Subjects were also marked with retroreflective hemispherical markers on specific landmarks, including head of the 5th metatarsal bones, most posterior part of the calcaneus, left and right PSIS, sacral spine (S2) and thoracic-lumbar spine (T12-L1). Trajectories of the markers on the feet were specifically used to define the stance phases, whereas the two markers on the spine were used to estimate trunk flexion-extension. Markers placement procedure was performed by a single operator in order to reduce the variability in the definition of the reference setting. Once placed sensor and markers, the subjects were instructed to rise from a chair (without armrests), walk on a straight line for 3 m (turning point was identified on the floor with the tape), turn 180°, walk back, turn 180° and sit down again (Fig. 1).

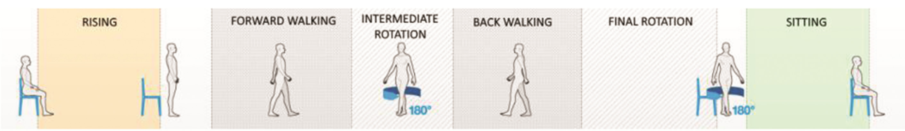


**Fig. 1.** Analyzed phases of the Timed-Up and Go (TUG) test.

The subjects performed the movement three times. Acceleration and angular rate data were acquired by using a dedicated software (G-Studio, BTS Bioengineering, Italy). Three-dimensional trajectories of each marker was also acquired by a dedicated software (SMART Capture, BTS Bioengineering, Italy). Synchronization between inertial sensor and optoelectronic system was performed by manually introducing an external shared trigger.

## 2.4 Data Analysis

Three-dimensional data from the optoelectronic system and inertial data (i.e. three-dimensional acceleration and angular rate), were processed using a software for multi-purpose biomechanical analysis (SMART Analyzer, BTS Bioengineering, Italy). After the definition a proper kinematic model, the different phases in TUG test were manually estimated as follows:

- **Chair Rising Start:** it corresponded to the beginning of the trunk flexion (estimated for both the systems on the first increase in the trunk flexion-extension velocity);
- **Chair Rising End:** it corresponded to the maximal trunk extension or, when it occurred before, to the first foot strike (estimated for both the systems on the first decrease in the trunk flexion-extension velocity or on the lowest value in the vertical component of the trajectories of the markers on the posterior calcaneus bones for the optoelectronic system and on the lowest value of antero-posterior acceleration for the inertial sensor);
- **Forward Walking Start:** it corresponds to the first foot strike after the chair rising (estimated on the lowest value in the vertical component of the trajectories of the markers on the posterior calcaneus bones for the optoelectronic system and on the lowest value of antero-posterior acceleration for the inertial sensor);
- **Forward Walking End = Intermediate Rotation Start:** it corresponds to the beginning of the rotation movement (estimated by using the angle between the pelvis and the global reference for the optoelectronic system and on the vertical component of the angular rate for the inertial sensor);
- **Intermediate Rotation End = Back Walking Start:** it corresponds to the conclusion of the rotational movement and to the beginning of the back walking phase (estimated between the pelvis and the global reference for the optoelectronic system and on the vertical component of the angular rate for the inertial sensor);
- **Back Walking End = Final Rotation Start:** it corresponds to the beginning of the rotational movement (estimated between the pelvis and the global reference for the optoelectronic system and on the vertical component of the angular rate for the inertial sensor);
- **Final Rotation End:** it correspond to the conclusion of the rotational movement (estimated between the pelvis and the global reference for the optoelectronic system and on the vertical component of the angular rate for the inertial sensor);
- **Chair Sitting Start:** it corresponded to the beginning of the trunk flexion (estimated for both the systems on the first increase in the trunk flexion-extension velocity).
- **Chair Sitting End:** it correspond to the complete trunk extension (estimated for both the systems on the first decrease in the trunk flexion-extension velocity).

Data analysis included the identification of the times of start/end and duration of each phase for both the systems. Values of shift in time and variations in duration for each phase were used to evaluate the RMS deviation between the measurements performed with the inertial sensor – considering the three different placements – and the values obtained by using the optoelectronic system. Furthermore, bias, lower and upper limits from Bland-Altman test were used also to investigate statistical agreement between the two methodologies.

## 3 Results

Figure 2 reports an example of the data acquired during the test including accelerations and rotations for the inertial sensor and trunk flexion-extension for the optoelectronic system.

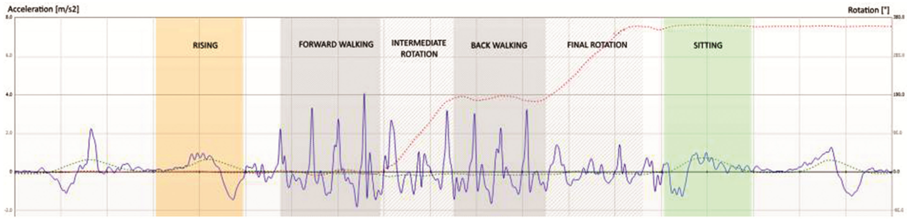


**Fig. 2.** Example of inertial data and phases segmentation. Antero-posterior acceleration (blue line) and rotation around vertical axis (red line) are reported. (Color figure online)

RMS deviation in start/end events and phase durations are reported in Fig. 3.

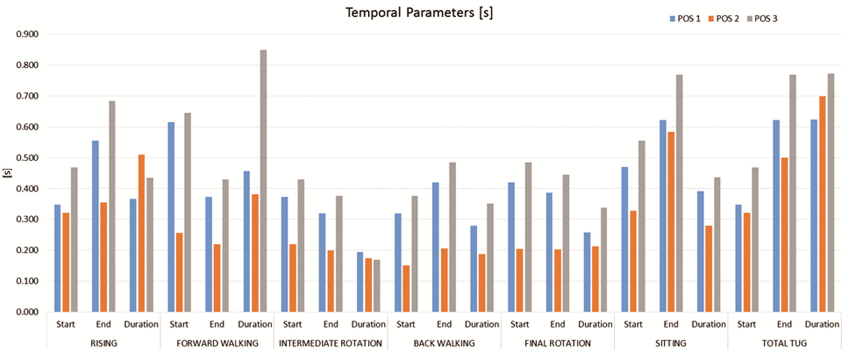


**Fig. 3.** Root Mean Square (RMS) deviation in start/end events and phase durations.

Average RMS deviations were 0.367 ± 0.144 s, 0.349 ± 0.196 s and 0.479 ± 0.245 s, for POS 1, POS 2 and POS 3, respectively. Average bias [with lower and upper limits] for phase durations were 0.112 ± 0.244 [−0.478 ± 0.372; 0.702 ± 0.252] s, 0.183 ± 0.212

[−0.372 ± 0.252; 0.738 ± 0.375] s and 0.202 ± 0.307 [-0.561 ± 0.388; 0.965 ± 0.530] s for POS 1, POS 2 and POS 3, respectively.

## 4 Discussion

In this study, we investigated the reliability of using an inertial sensor to identify the different phases present in the standard TUG test, considering three different placements on the lower-back part of healthy subjects and comparing the start/end events and durations with the values identified by using a validated motion analysis methodology. RMS deviations for the duration of the overall TUG test and for the rising phase - which is one of the most important parameter used in diagnosis - reported values that are low, even if higher with respect to the findings identified in literature [11, 32]. Furthermore, Bland-Altman analysis reported good level of agreement with low value of bias. In general, the durations of each phase are almost identical for the two methodologies with negligible differences even if the methodology based on the inertial sensor was inclined to underestimate them. From the point of view of sensor placement, we found that POS 2 (i.e. just beneath the lumbar-sacral joint) reported the lower values of RMS deviation with respect to the optoelectronic system for all the analyzed parameters with the exception of the overall TUG duration which, as previously reported, was more influenced by the last phase. This finding could be due to the specific performed motion, which affected more the lower part of the subject's back, corresponding to POS 2. Anyhow, considering overall duration POS 1 was the most reliable. Considering also the Bland-Altman analysis, POS 2 reported the narrowest range concerning limits of agreement averaged for all the phases, whereas POS 1 reported the lowest bias values. Considering the importance of estimating also kinematic parameters, unlike POS 2, POS 1 - being not influenced by the pelvic tilt - could allow to easily identify also flexion-extension movement of the lumbar part, which is fundamental in TUG test, especially during rising/sitting phases.

## 5 Conclusion

This study sought to shed a light on the reliability of using an inertial sensor during TUG test, with respect to the placement of the sensor itself. This issue is fundamental whenever clinical data about mobility and balance in elderly are required both in a clinical context and during domiciliary assessment. Furthermore, the use of a wireless wearable sensor can be thus optimized to be extended towards the possibility to use ubiquitous solutions with different kinds of data acquisitions, sharing and available information, including subject's kinematics.

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