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Empowering a Gait Feature-Rich Timed-Up-and-Go System for Complex Ecological Environments

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***Abstract*—Identifying fall risk can prevent injuries in the elderly as well as reduce the related financial burden. A balance assessment, Timed Up and Go (TUG), has been widely applied to estimate fall risk. However, the standardized TUG usually excludes complex factors (e.g. slopes and obstacles) falling short of representing challenges in environments that many older adults navigate. Having information on the motor performance in more complex settings can better inform clinicians about an individual's risk of falling. To this end, we present Smart Insole TUG (SITUG), a cost-efficient, real-time and self-assessment system suitable for the complex environmental TUG. Based on the human stride mechanism, our SITUG educes *four* refined aspects in the gait feature and segments the TUG process by *six* detailed phases, providing accurate and advanced information for the fall risk estimation. We evaluate the system with *four* complex environmental TUG. The results show that the SITUG achieves mean accuracy 94.1% in extracting subcomponents within a stride and 93.13% in deriving the stride length based on the verification of estimated walking distance. Moreover, this system can distinguish *six* TUG phases with the correctness around 90%.**

I. Introduction

About 14.5% of the U.S. population, around 46.2 million people, can be classified as a senior in 2014. By 2060, there will be more than twice that number, i.e., approximately 98 million elders in the US [1]. With the growing elder population, a health-related risk, fall risk, increasingly draws attention. Falls are the leading cause of injuries in older population. According to statistics from the National Council on Aging (NCOA), a senior receives emergency services every 11 seconds because of a fall and an elder dies every 19 minutes due to a fall [2]. The U.S. Bureau of Labor Statistics (BLS) reported $238,610$ nonfatal injuries and illnesses cases involving falls, slips, trips in 2015 [3]. The financial burden associated with falls is not optimistic either. The total fare of fall injuries was 34 billion U.S. dollars in 2013 and there exists an increasing trend with this financial cost [2].

Complex conditions of daily life which involve external, situational, and other factors can contribute to falls [4]. For examples, slopes and clutters are two extrinsic factors that can increase the fall risk [5]. Considering many older adults have a diminished ability to control their balance well, these conditions can place greater postural control and mobility demands on elderly individuals. Thus, complex elements from the living environment place many seniors at increased risk for falling [6]. Timed Up and Go (TUG) is recommended by the American Geriatric Society and the British Geriatric Society for evaluating balance, gait, and fall risk [7]. However, the standardized TUG and its widely adapted variations may not be as comprehensive as desirable to fully evaluate an individual's fall risk. These TUG forms are mainly criticized in three aspects: (1) They avoid many complex factors in fall scenarios that further test subject's abilities in braking, mobility, and balance in the human gait. (2) The measurement is only based on the total duration of TUG, offering thin test data, that can be deficient for the further fall risk assessment. (3) The presence of clinicians timing the TUG may provide a sense of security to patients or conversely, cause pressure to perform well, both of which can affect the result of TUG. Therefore, a robust, feature-rich and self-assessment TUG measuring system offers improvements in the fall risk analysis.

In this paper, we introduce Smart Insole TUG (SITUG), which can provide the real-time, fine-grained results of TUG in more complex ecological environments for the fall risk evaluation. Four complex environmental TUGs involving elements, such as the obstacle and the incline, are developed and deployed. Consisting an unobtrusive wearable sensing device, a matched smartphone software, and a competent TUG data analysis module in a cloud server, our SITUG is capable of extracting rich gait related features, providing advanced information about the walking status. Based on these features, the system can further analyze the complex environmental TUG by distinguishing six different TUG phases.

II. Preliminaries

A. Timed Up and Go Test

Timed Up and Go (TUG) is widely used for assessing the subject's mobility. In the standardized TUG, a subject is required to get up from the chair without using arms (the beginning of TUG), walk a 3-meter distance in a comfortable pace on flat ground, turn around, walk back to the chair, and turn again to sit back down (the end of TUG) [8]. The traditional setup needs a chair, a tape measure, a stopwatch, and someone to time the test process. The tape measure is used to indicate the three meters distance. The performance of the testee on the TUG is determined by the total duration [9]. As the judgment only depends on the time performance, the kinematic data is not recognized leading to lost information in the fall risk assessment when using the standardized TUG. In addition, the presence of clinician timing the TUG may

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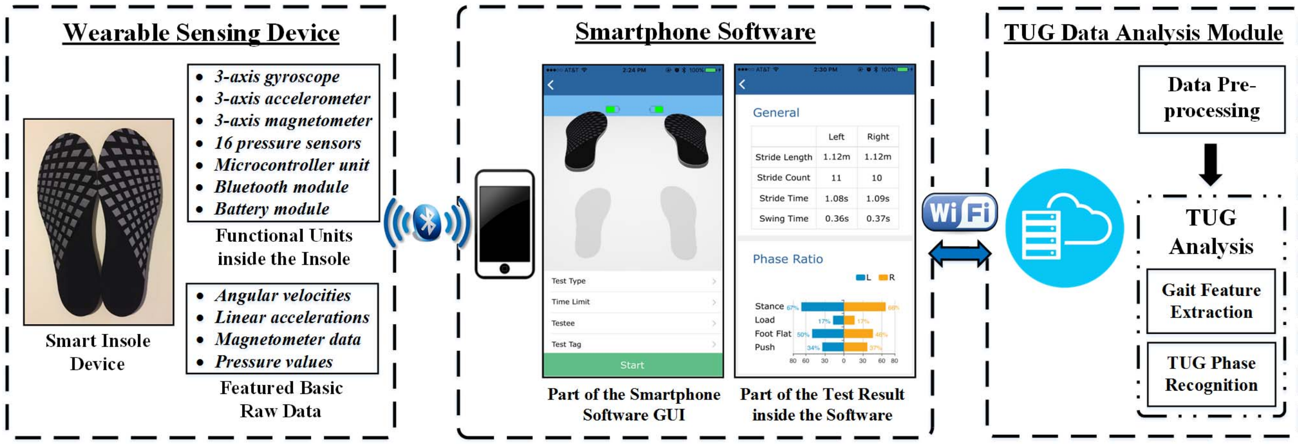

Fig. 1. The overall framework of our proposed system, SITUG. It contains a wearable sensing device, the smart insole, a matched smartphone software, and a TUG data analysis module within a cloud server. The photo of the actual smart insole device are presented under *Wearable Sensing Device*. Pictures of the smartphone app are placed under *Smartphone Software*.

influence the performance. It is possible that the test setting could cause the client anxiety or have the opposite impact giving the client a sense of security with the clinician standing nearby. To address these issues, several technology-based methods for measuring TUG data are developed including video-based and IMU-based ones.

B. Advanced TUG Measurement

The video-based TUG measurements allow testees to perform the TUG without the presence of a tester [10]. In some advanced studies, the total taken steps and the duration of some phases (e.g., turning and sitting down) in the TUG can be extracted automatically via video cameras [11], [12]. Knowing the time taken in different TUG phases improves the reliability of estimating the fall risk [13]. However, the video-based methods have obvious drawbacks and limitations in practical usages. The camera setup is crucial. The position of cameras and the lighting of environments must be carefully adjusted. There are also privacy issues if we apply them to residential environments.

The IMU-based way utilizes the inertial measurement units, an electronic device which contains accelerometers, gyroscopes, and more, offering detailed basic data including linear accelerations and angular velocities [14]. Many existing IMU-based systems provide finer data of the TUG process. However, they require either bulky devices or obtrusive sensor attachments. For instance, a reliable instrumented system developed by Salarian *et al.* [15], named iTUG, needs seven sensor attachments over the entire body. Another well-developed system, QTUG [16], depends on only two small sensors, but deploys an inconvenient tablet comparing to smartphones.

C. Design Consideration and Goal

In additional to the aforementioned issues, another three common deficiencies exist in most of the current advanced TUG systems, (1) handling only the standardized TUG with no complex factor, (2) missing analyses in some TUG aspects, and (3) difficulties in accessing test results in real-time. To address the existing shortages, our SITUG design should satisfy the following requirements:

- Unobtrusive: the SITUG has no sensor attachment to the body or camera setup nearby.
- Cost-efficient: the system is built based on low-cost functional units.
- Robust: our SITUG is practical for the complex environmental TUG.
- Reliable: It captures accurate features in all complex environmental TUG aspects.
- Real-time: It provides real-time test results inside the smartphone software.

III. Approach Overview

As shown in Fig. 1, our system comprises of a wearable sensing device, a smartphone software, and a TUG data analysis module. The wearable sensing device, named Smart Insole, collects basic data such as angular velocities, linear accelerations, and pressures, during the performance of the test. The smartphone software is mainly acting as a bridge between the sensing device and the TUG data analysis module. The Smart Insole receives commands for data collecting from and transfers obtained data to the software, which uploads raw data files to our TUG data analysis module located in the cloud server for operating the data pre-processing and the TUG analysis. At the end of this process, test results are sent to the smartphone software. Furthermore, a database included in the cloud server is capable of saving the physical information and test histories for each user. The following are the detailed descriptions of different modules.

A. Smart Insole

Our wearable sensing device shown in Fig. 1, the Smart Insole, has been commercialized by SennoTech Inc. [17]. It has a similar hardware design to its previous version [18], [19]. This insole has three essential functions. The first one is the data sensing accomplished by a 3-axis gyroscope, a 3-axis accelerometer, a 3-axis magnetometer, and 16 pressure sensors. Secondly, the data acquiring is performed by a 16 to 1 channel MUX and a Microcontroller Unit (MCU). Finally, the data transferring is done using a Bluetooth Low Energy (BLE) module. This device also contains a battery module which is charged through USB connection. All the aforementioned components except the pressure sensors are placed in a 40mm by 40mm printed circuit board (PCB).

B. Smartphone Software

The smartphone software makes the entire system user-friendly. We designed it by prioritizing ease-of-operation considering most users are elders who may have less experience with smartphone apps compared to other age groups. The software connects the Smart Insole through Bluetooth so that testees can choose when to collect data by simply clicking a button. The design of the smartphone software's graphical user interface (GUI) is shown in Fig. 1. Our software automatically transfers data from the insole to the cloud server for running the TUG data analysis module, via Wi-Fi or LTE. Moreover, the subject's physical information and all test results can be viewed inside the software, as presented in Fig. 1.

C. TUG Data Analysis Module

The TUG data analysis module located at the cloud server is the core part in our system design. It has two main missions, the data pre-processing and the TUG analysis. This module performs three activities for the data pre-processing [20]: (1) denoising collected pressure values, (2) calibrating and filtering accelerometer and gyroscope data, and (3) initializing the baseline with magnetometer data. After the above described procedure, we obtain finer basic data for the TUG analysis including two functional features, the gait feature extraction and the TUG phase recognition. For a clearer illustration, the structure of the TUG analysis is presented in Fig. 2 and the methodology is fully described in the next section.

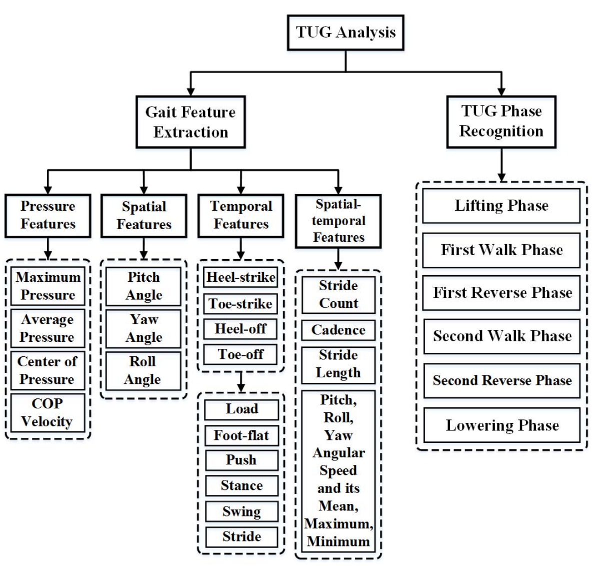

Fig. 2. The structure of TUG analysis including two functional features, the gait feature extraction and the TUG phase recognition.

IV. Fine-grained TUG Analysis

A. Gait Feature Extraction

We consider our extracted gait features into four subdivisions including pressure, temporal, spatial, and spatial-temporal ones. The pressure and spatial features are bases for the temporal feature extraction. In particular, the former provides data in the walking balance [21]; and the latter gives a comprehensive picture of plantar positions and motions. The temporal feature shows the time information of detailed activities within the gait. Combining the spatial and temporal data, the spatial-temporal feature is significantly helpful in the fall risk evaluation [22].

1) Pressure Feature:

- **Maximum Pressure:** the maximum out of 16 pressure values taken by all sensors in one sample intake.
- **Average Pressure (P_{avg}):** the average pressure on the sole or two particular areas, the fore (toe) and the hind (heel), in one sample intake, calculated by:

$$P_{avg} = \frac{\sum_i^m P_i}{n}, \quad n \in \{4, 16\}, \tag{1}$$

where P_i is the pressure value of i^{th} sensor. The i starts from the index of first sensor in a partial or entire plantar area and ending at m, the index of last sensor in this area. The n denotes the number of involved pressure sensors in the calculation. Sensors with the index 1 to 4 are located at the fore area. The last four sensors with the index 13 to 16 are on the hind area.

- **Center of Pressure** (COP) **Location** (X_{cop}, Y_{cop})**:** the position of COP on the sole in one sample intake.

$$X_{cop} = \frac{\sum_i^n X_i P_i}{\sum_i^n P_i}, \quad Y_{cop} = \frac{\sum_i^n Y_i P_i}{\sum_i^n P_i}, \tag{2}$$

where $n = 16$, the total amount of pressure sensors. The X_i and the Y_i are representing coordinate values for the i^{th} pressure sensor .

- **COP Velocity (V_{cop}):** the speed of COP location movements during the time interval $\triangle t$.

$$V_{cop} = \frac{1}{\triangle t}\sqrt{(X_{dist})^2 + (Y_{dist})^2}, \tag{3}$$

where the COP travel distances on both X and Y axes are defined as follows:

$$X_{dist} = |X_{cop}(t + \triangle t) - X_{cop}(t)|, \tag{4}$$

$$Y_{dist} = |Y_{cop}(t + \triangle t) - Y_{cop}(t)| \tag{5}$$

2) Spatial Feature: This feature extraction is enabled by applying the pitch, roll, and yaw axes on the Smart Insole. Angles caused by rotations around the axes can be used to monitor movements of feet. The following calculations are inspired by an online article [23].

- **Pitch Angle (θ):** the angle caused by the plantar rotation about the pitch axis is equal to the one between vector $\vec{P}$

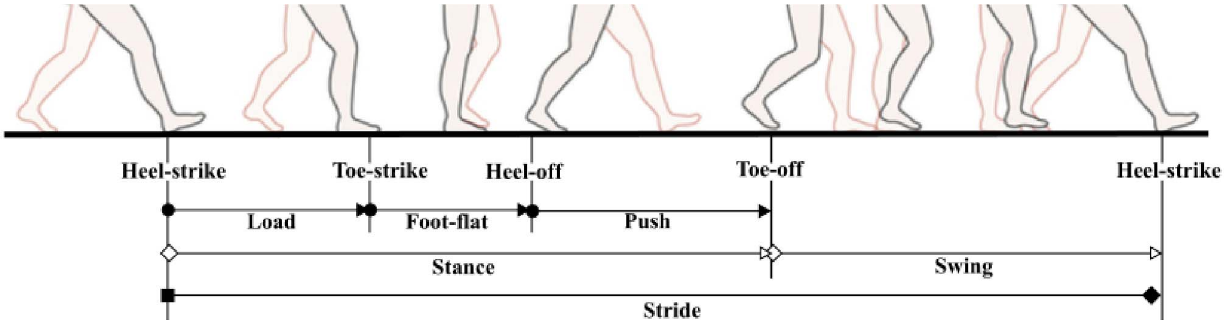

Fig. 3. Phases in a stride including the stance and the swing. The stance is consisted by a load, a foot-flat, and a push sub-phases, which are separated by four essential moments, heel-strike, toe-strike, heel-off, and toe-off. The swing starts from a toe-off and ends at a following heel-strike.

and its projection vector $\vec{P}'$ on the xy-plane or we could say the ground.

$$\vec{P} = (a_x, a_y, a_z), \tag{6}$$

where the $\vec{P}$ represents the plantar direction and position; the a_x, a_y, and a_z are linear acceleration values on x-, y-, and z-axes in the corresponding sample intake. The equations for calculating the θ are given below:

$$||\vec{P}'_{xy}|| = \sqrt{(a_x)^2 + (a_y)^2}, \tag{7}$$

$$\theta = \arctan(a_z \times (||\vec{P}'_{xy}||)^{-1}), \tag{8}$$

where $||\vec{P}'_{xy}||$ is the magnitude of $\vec{P}'$ on the xy-plane.

- **Roll Angle** (ψ)**:** the angle caused by the plantar rotation about the roll axis is obtained ψ by computing the angle between the z-axis and the $\vec{P}'$ on the yz-plane.

$$\psi = \arctan(a_y \times (a_z)^{-1}) \tag{9}$$

- **Yaw Angle** (ϕ)**:** the angle caused by the plantar rotation about the yaw axis is derived from calculating the one between the x-axis and the $\vec{P}'$ on the xy-plane.

$$\phi = \arctan(a_y \times (a_x)^{-1}) \tag{10}$$

3) Temporal Feature: Four essential moments including a heel-strike, a toe-strike, a heel-off, and a toe-off are exactly the breaking points for phases and subphases in a stride (see in Fig. 3). Methods for finding the four moments are referred from Mariani *et al.* [24].

- **Heel-strike (HS):** the moment of the heel striking the ground during the walking. Upon each HS, the average pressure of hind area suddenly and dramatically increases from zero. Therefore, the SITUG stamps the HS by searching critical points (CP) in the derivative of P_{avg}, denoted as $(P_{avg})'$, of hind area [21]. Moreover, it checks the derivative of pitch angle, $(\theta)'$, to verify the CP found in the $(P_{avg})'$. The $(\theta)'$ is less than zero and should be a local minimum upon an HS.
- **Toe-strike (TS):** the moment of the toes hitting the ground. Before a TS, $P_{avg} = 0$ in the fore area. After the TS, this P_{avg} gradually increases. Based on this trend, the system locates a TS by searching a time stamp that the P_{avg} of fore area is zero until reaching it and increasing to positive afterward. In addition, our SITUG uses the $(\theta)'$ for the verification. A TS is found if the $(\theta)'$ is less than and close to zero at the located time stamp.
- **Heel-off (HO):** the moment the heel is disconnected with the ground by lifting. The system first tracks the $(\theta)'$ and locates a time stamp where the $(\theta)'$ starts to continuously decrease from around zero until reaching another local minimum. If $P_{avg} = 0$ in the hind area on this time stamp, then it is an HO.
- **Toe-off (TO):** the moment of the toes lifting apart from the ground. A TO is marked by finding the time point of first zero value in the $(\theta)'$ behind its last local minimum as mentioned in locating the HO. Furthermore, $P_{avg} = 0$ in the fore area upon a TO.

Finding the above four moments, the duration of a stride's phases (e.g., a stance and a swing) as well as periods of three subphases in the stance (e.g., a load, a foot-flat, and a push) can now be derived [21], [24].

- **Duration of Load:** the foot is lowering down with the pivot located at the heel.

$$T(Load) = t(TS) - t(HS), \tag{11}$$

where T and t denotes the duration and the time stamp.

- **Duration of Foot-flat:** both the heel and the toes are connected with the ground.

$$T(Foot - flat) = t(HO) - t(TS) \tag{12}$$

- **Duration of Push:** the foot is lifting up with the pivot located under the toes.

$$T(Push) = t(TO) - t(HO) \tag{13}$$

- **Duration of Stance:** a load, a foot-flat, and a push form a stance.

$$T(Stance) = t(TO) - t(HS) \tag{14}$$

- **Duration of Swing:** a certain walking distance is made by swinging a leg forward.

$$T(Swing) = t(HS^{next}) - t(TO) \tag{15}$$

- **Duration of Stride:** a stride, also called a gait cycle, includes two subdivisions, a stance and a swing.

$$T(Stride) = T(Stance) + T(Swing) \tag{16}$$

4) Spatial-temporal Feature:

- **Stride Count:** the amount of strides that happened within the entire TUG.
- **Cadence:** the amount of strides taken in one minute.
- **Stride Length:** the walking distance produced in a stride is calculated by taking the double integral of x-axis linear acceleration in the corresponding time section.
- **Pitch, Roll, Yaw Angular Speed** (V_θ, V_ψ, V_ϕ)**:** the derivative of pitch, roll, yaw angle.
- **Mean, Maximum, and Minimum** V_θ, V_ψ, V_ϕ

B. TUG Phase Recognition

Considering each TUG into six phases, we derive the further information, such as the time taken during the turning, that is highly useful in the fall risk measurement [22]. For a clearer illustration, we introduce twelve time stamps which directly mark all the six phases. These temporal points are grouped and described below:

1) Lifting Phase (LF):

- **Beginning of TUG (BOTUG):** BOTUG is also the beginning of LF. It is the moment of starting to press feet onto the ground and trying to get up from the chair. If the testee sits naturally, $P_{avg} = 0$ on the entirety of both soles. Both P_{avg} start increasing when the testee tries to stand up and presses both feet onto the ground; therefore, the first time when $P_{avg} > 0$ in both entire plantar areas, the SITUG locates the BOTUG.
- **Ending of Lifting (EOL):** EOL is the moment of reaching a full-stand (up-right) posture after the BOTUG. Both soles' P_{avg} keep increasing before the EOL and stay in a small range of values afterward until the beginning of the next phase (BOW-1) arrives. Our system indicates the EOL by finding the first temporal point with the following three properties: (1) $P_{avg} > 0$, (2) $(P_{avg})'$ close or equal to zero, and (3) the second derivative of P_{avg} is less than zero. If the SITUG cannot locates the EOL before the BOW-1, these two are overlapped.

2) First Walk Phase (FW):

- **Beginning of First Walk (BOW-1):** the first series of an HO, a TO, and an HS implies the first step has taken and the walking has started. Thus, our system detects this first series and locates the BOW-1 that is the HO.
- **Ending of First Walk (EOW-1):** EOW-1 is the moment of finishing a short distance followed by a turning. If the SITUG has marked the beginning of next phase (BOR-1), the EOW-1 is the last TS right before the BOR-1.

3) First Reverse Phase (FR):

- **Beginning of First Reverse (BOR-1):** the turning in the FR is unique, which can be detected if both feet successively satisfy $D \geq 75°$, where

$$D = |(\phi)_{current} - (\phi)_{last}| \tag{17}$$

The $(\phi)_{current}$ represents the yaw angle upon the current TS and the $(\phi)_{last}$ is the one upon the last TS. The BOR-1 is a TO located right after the first TS among two pairs of a current and a last TS, performed by both feet.

- **Ending of First Reverse (EOR-1):** if the system finds conditions of detecting the BOR-1 no longer satisfied, the FR has ended. Within the last two pairs of TS qualified for the conditions, the final TS is the EOR-1.

4) Second Walk Phase (SW):

- **Beginning of Second Walk (BOW-2):** BOW-2 is the moment of starting to walk back after the FR. The SITUG sets the first TO after the EOR-1 as the BOW-2.
- **Ending of Second Walk (EOW-2):** EOW-2 is followed by the last turn in front of the chair. Similar to the case of locating the EOW-1, the last TS before the beginning of second reverse is the EOW-2.

5) Second Reverse Phase (SR):

- **Beginning of Second Reverse (BOR-2):** BOR-2 is the first TO behind the foremost TS in the final two pairs of TS as described in Section IV-B3 with $D \geq 20°$ because only the regular turning happens in the SR.
- **Ending of Second Reverse (EOR-2):** our system stamps EOR-2 by checking the pitch and the yaw angular speeds of both feet. Once these speeds become and remain closely around zero, the EOR-2 is marked since no step is taken after it.

6) Lowering Phase (LW):

- **Beginning of Lowering (BOL):** during the process of sitting down, the P_{avg} of hind area, $(P_{avg})_{hind}$, is distinctly greater than the one of the fore area, $(P_{avg})_{fore}$. Our system marks the BOL after the EOR-2 if $(P_{avg})_{hind} \geq (P_{avg})_{fore} \times 15$ in both plantar sample intakes.
- **Ending of TUG (EOTUG):** EOTUG is also the end of LW. If the P_{avg} and the x-axis linear acceleration of both feet are all equal to zero, the EOTUG is found.

V. Evaluation

A. Experimental Setup

Four different complex environmental TUG are operated in order to verify the capability of SITUG. The data set is collected by the Smart Insole placed in shoes with 100 Hz as the sampling frequency and 12-bit as the resolution. The video filming is used with the purpose of setting ground truth references. Two healthy female and four male subjects, measured in weight from 57 - 89 kg and height from 163 - 186 cm, volunteered to carry out the series of four complex environmental TUG (see in Fig. 5).

- Extended TUG (E-TUG): E-TUG has the similar setup to the standardized TUG except that the distance between the start and the turning locations is extended from three to seven meters as presented in Fig. 4(a).
- Incline TUG (I-TUG): testees need to walk on an incline within I-TUG. Some activities (e.g., turning, standing up, and sitting down) are still performed on the flat ground. Fig. 4(b) shows the process of I-TUG.
- Bypass TUG (B-TUG): B-TUG is operated on the flat ground. Each subject should avoid obstacles by passing aside in the test (see in Fig. 4(c)). The displacement is

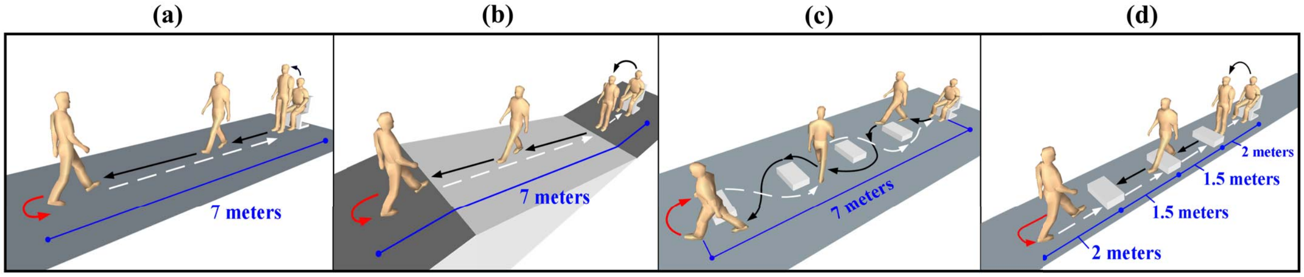

Fig. 4. Four different complex environmental TUG including: (a) E-TUG: standardized TUG with the extended distance; (b) I-TUG: TUG with the incline factor; (c) B-TUG: TUG with the obstacle factor. Testees should go around obstacles; (d) O-TUG: Testees should step over obstacles.

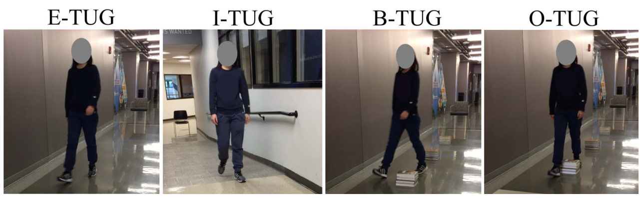

Fig. 5. The experimental scenes of four complex environmental TUG.

seven meters and the estimated walking distance is 7.75 meters between the start and the turning points.

- Overpass TUG (O-TUG): in O-TUG, the subject avoids obstacles by stepping over as shown in Fig. 4(d). Detailed distances are also provided in the graphic of O-TUG.

We aim at validating the feasibility of SITUG in monitoring movements within the complex environmental TUG which is designed to create a more complex ecological environment. Moreover, we present contrasts found in the results of aforementioned four TUG for providing an overview image of SITUG in handling different test cases.

B. Feasibility Assessment

We use three terms to present the results of validation which are the accuracy, the absolute error E_a, and the relative error E_r. The corresponding equations are listed below:

$$E_a = V_m - V_t, \tag{18}$$

$$E_r = \frac{|E_a|}{V_t} \times 100\%, \tag{19}$$

$$Accuracy = (1 - \frac{|V_m - V_t|}{V_t}) \times 100\%, \tag{20}$$

where V_m and V_t stand for the measured and the true values.

1) Duration of Load, Foot-flat, and Push: As described in Section IV-A3, the load, the foot-flat, and the push duration are directly derived from four essential time stamps, an HS, a TS, an HO, and a TO, in a stride. We analyze the capability of SITUG in locating the four time points by checking the correctness of three extracted duration. Comparing the results found by the SITUG and observing video recordings, we obtain the average accuracy of load duration 92.9%, foot-flat duration 95.1%, and push duration 94.2%. The detailed comparisons between results found by the two different methods are shown in Fig. 6.

2) Stride Count and Stride Length: According to the comparison between stride count (SC) results of each testee in four different TUG derived from SITUG computations and video recording observations, the mean of all relative errors is 4.77%. Moreover, Fig. 7(a) provides a view of absolute errors of all extracted SC in four different TUG.

In order to assess the reliability of stride length (SL) results, we first estimate walking distances performed by each testee in four different TUG using the extracted SL. The walking distance (WD) is computed as follow:

$$WD = \frac{S_{left} + S_{right} + C}{2}, \tag{21}$$

where the S_{left} is the sum of all SL produced by the left foot and the S_{right} represents the one caused by right foot movements; the C is an average value of all SL. The WD is usually close to either the S_{left} or the S_{right}. Therefore, we use the mean value of S_{left} and S_{right} in the equation (21). Notice the SITUG does not consider the very first two steps, which has no beginning heel-strike, in the TUG as strides, we add $(\frac{C}{2})$ to better estimate the WD. Comparing the WD with the real walking distance of test setup, the correctness of SITUG in educing the SL is assessed. The maximum, the median, and the minimum accuracies of computed WD are 99.36%, 93.16%, and 81.43% as shown in Fig. 7(b).

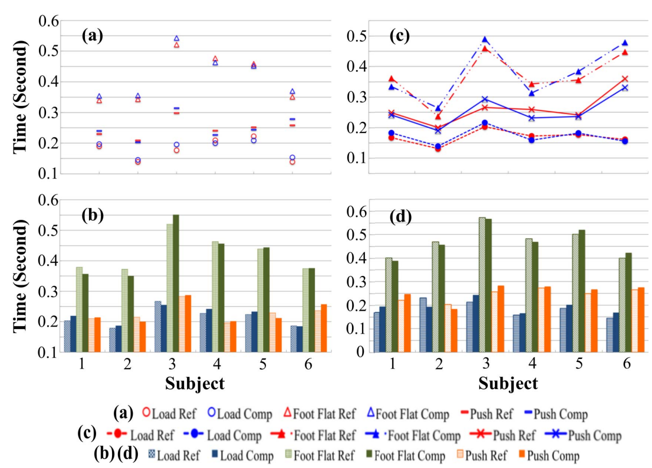

Fig. 6. The average load, foot-flat, push duration of each subject in (a) E-TUG, (b) I-TUG, (c) B-TUG, and (d) O-TUG. Labels with Ref: the duration obtained from the video observations. Labels with Comp: the duration computed by the SITUG.

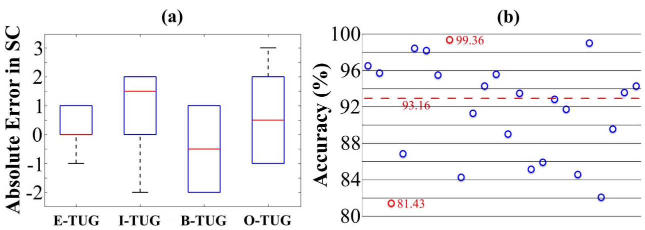

Fig. 7. (a): The maximum, the median, the minimum, and the IQR in absolute errors of extracted stride count from six subjects' TUG results. (b): Each circle represents an accuracy in estimating the walking distance (WD) of a subject in a TUG; the upper and the lower red circles are the maximum and the minimum; the red dash line indicates the median.

3) TUG Phases: To assess the correctness of recognizing TUG phases, we check the inferred average duration of each phase in four different TUG taken by all subjects with the reference value derived from video observations (see in Fig. 8). Mean accuracies of extracted six TUG phase duration are 94.78%, 91.17%, 82.04%, 90.23%, 84.39%, and 92.47%.

C. Comparison among Results of Different Types of TUG

1) The ratio changing patterns in each phase duration within a stride time are similar in the E-TUG, the I-TUG, and the B-TUG. However, the situation of O-TUG is completely different. In Fig. 9, we present the ratio of load, foot-flat, stance duration to a corresponding left foot stride period in the series of four TUG performed by one of our female testee. It is understandable that the pattern in the O-TUG is much more complicated than in the other three tests because the testee uses the arbitrary foot to step over each obstacle.
2) The change of cadence in the O-TUG process is distinct and it is worth mentioning that it has an unique sharp pattern. Cadence trends in the I-TUG and the B-TUG are either similar to the ones in the E-TUG or quite irregular. Therefore, Fig. 10(a)-(d) only show cadence changing paths of one female and one male subjects in the E-TUG and the O-TUG.
3) Due to the design of B-TUG, multiple regular turnings happen during the test. The yaw angle changing pattern is especial in the B-TUG as a regular turning is detected using equation (17) with $D \geq 20°$. In Fig. 10(e)-(h), each vertical line represents a result of a yaw angle value at the current toe-strike (TS) minus the one at the last TS. We only present the yaw angle changing patterns in the E-TUG and the B-TUG since trends of yaw angles in other two tests are close to the one in the E-TUG.

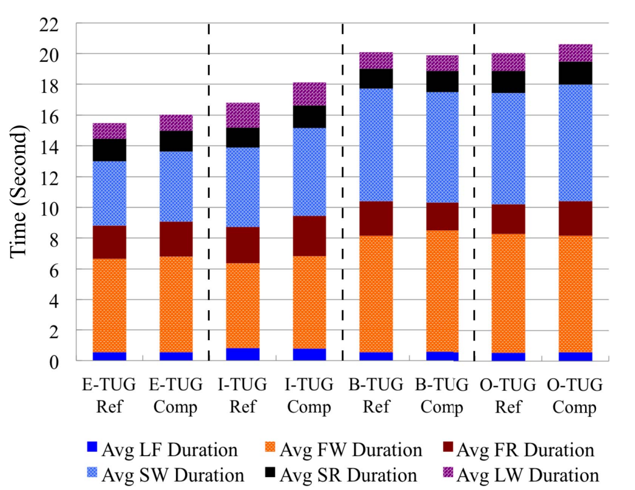

Fig. 8. The graph presented for the verification of extracted TUG phases. Each colored segment inside a column represents an average value of all duration of the corresponding TUG phase created by six subjects. Ref: true values from the video observation. Comp: our system's computed values.

VI. Conclusion and Future Work

Due to the existing drawbacks in current fall risk assessments, we propose the Smart Insole TUG (SITUG) designed for extracting rich and fine features in the Timed Up and Go in more complex ecological environments advances current clinical standards for identifying individuals at risk for falling. The SITUG consists of a sensor-equipped wearable device, a user-friendly smartphone software, and a well-considered TUG data analysis module. It offers comprehensive gait feature extractions and distinguishes six detailed TUG phases, providing fine-grained information for estimating the fall risk. According to the results from experiments, the SITUG can educe three subphase duration in the stance period with the overall accuracy above 92.9% and recognize all TUG phases with the mean accuracy around 90%. Moreover, it is competent in counting the number of strides with the average relative error 4.77% and estimating the walking distance with the mean accuracy 93.16% for verifying the computed stride length.

In the future, we plan to improve the system by two main paths. The first is enabling the SITUG in monitoring the TUG within the stairs environment. Secondly, we will evaluate the system in the wider and the older populations. Afterwards, we believe that our SITUG can achieve a higher level of usability and reliability in complex ecological environments.

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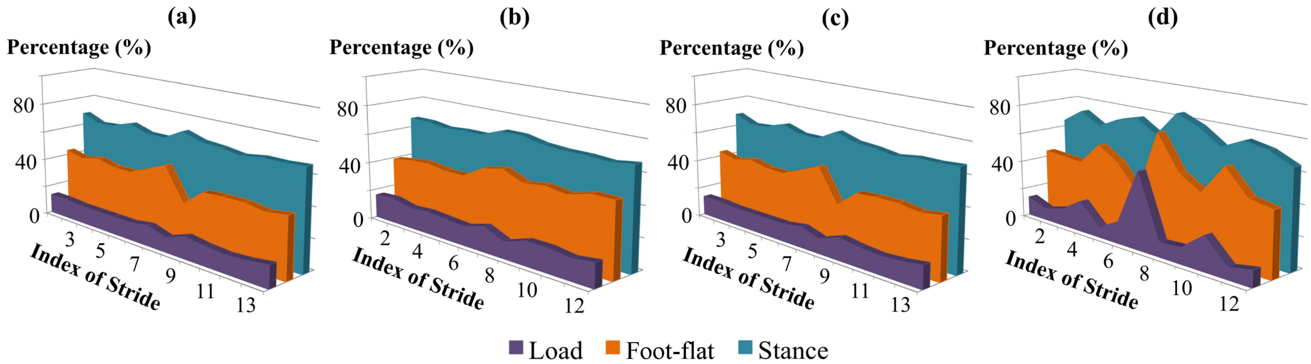

Fig. 9. The duration ratio of load, foot-flat, stance to a corresponding stride time in (a) E-TUG, (b) I-TUG, (c) B-TUG, and (d) O-TUG.

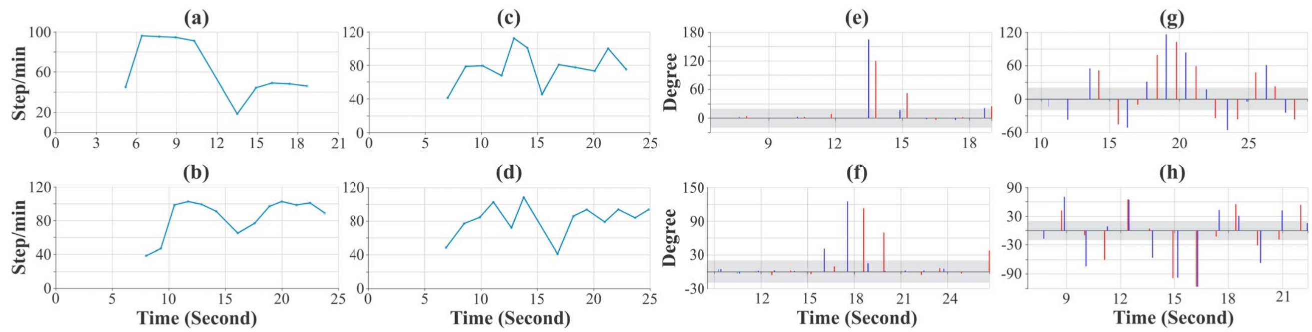

Fig. 10. The first and the second row of graphs are test results of a female and a male subjects. (a) and (b): the cadence changing pattern in the E-TUG. (c) and (d): the cadence changing pattern in the O-TUG. (e) and (f): yaw angle differences in the E-TUG. (g) and (h): yaw angle differences in the B-TUG. Each blue vertical line in (e)-(h) represents a disparity between yaw angles on the current and the last toe-strikes in the left plantar motion while a red line represents the one in the right plantar motion.

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