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Estimation of average and maximum daily-life mobility performance using the Timed Up-and-Go (TUG): Exploring the added value of an instrumented TUG

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Short Title: Estimation of daily-life mobility performance in community-dwelling older adults

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Motor capacity; mobility performance; TUG;

Abstract

Introduction:

The association between specific motor capacity variables obtained in a laboratory and parameters of daily-life mobility performance obtained via wearables is still unclear. The Timed Up-and-Go (TUG) test is a widely used motor capacity tests available either as traditional hand-stopped TUG or as instrumented TUG (iTUG) providing specific information about its subphases. This study aimed to: 1) estimate the association between the TUG and specific parameters reflecting average and maximum daily-life mobility performance (MP), 2) estimate the benefits of the iTUG in terms of explaining MP in daily life compared to the TUG.

Methods:

The present study was a cross-sectional analysis using baseline data of 294 older persons (mean age: 76.7 ± 5.3 years). Univariate linear regression analysis was performed to delineate the coefficient of determination between TUG time and participants' MP. MP variables containing mean cadence (MCA) to represent average performance and the 95th percentile of mean cadence of walks with more than three steps (p95>3stepsMCA) to represent maximum performance. To determine whether the iTUG variables give more information about MP, a stepwise multivariate regression analysis between iTUG variables and the p95>3stepsMCA variable to represent maximum performance was conducted.

Results:

The univariate regression models revealed associations of the TUG with MCA (adjusted $R^2 = .078$, $p<0.001$) and p95>3stepsMCA (adjusted $R^2 = .199$, $p<0.001$). The multivariate stepwise regression models revealed a total explanation of maximum daily life MP (p95>3stepsMCA) of the TUG (adjusted $R^2 = .199$, $p<0.001$) vs. iTUG (adjusted $R^2 = .278$, $p<0.010$).

Discussion/ Conclusion:

This study shows that the TUG better reflects maximum daily life MP than average daily life MP. Moreover, we demonstrate the added value of the iTUG for a more accurate estimation of daily MP compared to the traditional TUG. The iTUG is recommended to estimate maximum daily life MP in fall-prone older adults. The study is a step toward a specific assessment paradigm using capacity variables from the iTUG to estimate maximum daily life MP.

Introduction

Understanding the association between what people are able to do during a specific motor assessment in a standardized environment and what people do in their daily life is important in order to develop specific laboratory-based assessments capturing relevant aspects of daily functioning [1]. The International Classification of Function, Disability, and Health (ICF) [2] discriminates between assessments measuring motor capacity (MC), which is indicative of the highest possible level of functioning of an individual in each moment in time, and in contrast, real-life assessments measuring mobility performance (MP) which is what an individual does in their current environment. Typically, MC tests are conducted in standardized settings, often using stopwatch timing, or counting repetitions of movements or tasks [1].

In clinical practice, MC measures (e.g., habitual gait speed) are often used to draw conclusions on subjects' MP and functionality in real life, reflecting their performance beyond the time of the assessment [3]. This is crucial as clinical decisions leading to subsequent therapeutic interventions or the initiation of a rehabilitation chain are often based on such laboratory-based test results [3]. However, previous studies show that MC measures in older adults such as habitual gait speed have limited value for predicting MP in real-life [4–8]. In other words, the relationship between MC and MP is not straightforward. Among several factors influencing the association between MC and MP habitual vs. maximal performance conditions have been identified as important factors. For example, gait parameters measured in the laboratory, (e.g., 4m gait speed, cadence) reflect a person´s best MP rather than their average MP [9]. More specifically, older people's habitual gait speed measured in the laboratory is more closely related to the maximum gait speed than to average gait speed in the real world. This could be explained by the fact that walking under laboratory conditions can increase the awareness of being observed, which is known as the Hawthorne effect [10]. Current research has focused on the MC-MP association with a focus on laboratory-based assessment of gait speed [9, 11, 12].

In contrast, the relationship between the Timed-Up-And-Go (TUG) and average and maximum MP measures, which represent real life performance, is less clear. This is surprising as the TUG is a widely used laboratory-based capacity test to evaluate mobility performance and proactive balance control [13]. Compared to habitual gait speed, the TUG includes key motor functions in addition to habitual gait speed, such as getting up and sitting down from a chair, which are highly important for daily life [18]. The TUG is easy to administer and able to discriminate between fallers and multiple fallers [14]. Therefore, it is of clinical importance to understand the relationship between TUG and real-life performance. Longer TUG times have been associated with impaired mobility and an increased fall risk in older patients and patients with Parkinson’s disease or stroke [15–17]. The TUG consists of four subcomponents (sit-to-stand, gait, turning and turn-to-sit), that have an essential meaning for the patient´s daily life [18]. A drawback is that the traditional TUG solely looks at the total time to complete the test without separating the subject´s performance into the four individual components [19] although there is additional clinical information to be drawn from data on the subcomponents. However, total TUG time is not necessarily, and at most only very slightly, associated with the performance of the specific subcomponents [18].

As a result, the TUG only provides limited information about the underlying reasons for reduced total performance [18, 20]. For example, it has been found that the features that capture the turning phases are particularly relevant, as they may be important for predicting balance and they have been shown to be particularly sensitive as they may explain impaired motor control in patients at risk of falling and/or those with mild cognitive impairment [21, 22]. This is because the turning task with its asymmetric characteristics of the turning phases requires a certain amount of turning speed, stride length, stride width and precise control of the individual limbs in order to keep the centre of gravity between the two feet. For this reason, the turning task particularly endangers the patient's postoral control, e.g. in patients with Parkinson's disease. The new, instrumented version of the TUG (iTUG) aims to overcome the aforementioned limitations by using inertial sensors to compute a set of spatial and temporal features from different subphases [23] of the iTUG that can be used to examine the quality of the task in more detail [21, 22]. The iTUG can compute specific features for the turning phases, such as the Mean Velocity Turn to Sit, Peak Velocity, or turning duration [21]. Overall, the iTUG is able to compute a high number of features [24]. Through a factor analysis, Coni et al. were able to reduce the dataset to 38 instrumented features (Tab. 5) with a clear clinical meaning, which were grouped into eight factors [24]. The eight factors of the interpretative model according to Coni et al. are “walking ability”, “postural transitions intensity anterior-posterior direction”, “sit-to-walk smoothness”, “turn-to-sit smoothness”, “turning ability”, “global fitness”, “turn-to-sit intensity vertical direction”, “sit-to-walk intensity medio-lateral direction”. Based on the underlying instrumented features of these factors that provide additional information, we hypothesise that the iTUG may add more value to the explanation of daily life mobility performance than the TUG. The aim of the present study was to investigate (1) the association between the TUG and specific parameters reflecting average and maximum daily-life MP and to (2) estimate the benefits of the iTUG in terms of explaining MP in daily life compared to the TUG.

~~For aim (1) we hypothesised that the TUG would show a greater association with maximum MP compared to average MP. For aim (2), we hypothesised that the iTUG would explain a greater amount of coefficient of determination in MP compared to the traditional TUG.~~

Material and Methods

Population

Baseline data of the LiFE-is-LiFE trial [25] were analyzed. Community-dwelling older adults aged 70 years who were 1) cognitively intact (Montreal Cognitive Assessment [MoCA] ≥ 23 points [26]), 2) able to walk 200 meters (with a walker if needed), and 3) did not exercise more than once per week or engage in more than 150 minutes per week of moderate to vigorous physical activity in the past 3 months, and 4) at risk of falls were included. Detailed information about the inclusion and exclusion criteria is provided elsewhere [25]. Prior to participation, all participants provided written informed consent. Ethical approval was given by both responsible Ethic Review Boards of the two study centers (Heidelberg and Tübingen, Germany). The study agreed with the Declaration of Helsinki.

Descriptive Measures

Demographic and clinical characteristics including age, sex, height, Body-Mass Index (BMI), number of comorbidities, number of medications, % of fallers in past six months [27], cognitive status (MoCA), subjective capacity (Late-Life Function and Disability Instrument [LLFDI]) [28], fear of falling (Falls Efficacy Scale-International, 7-item version [Short-FES-I]) [29], and balance self-efficacy (Activities-specific Balance Confidence Scale [ABC-Scale]) [30] were collected.

TUG and iTUG

During the TUG, participants were asked to stand up from a standard chair with armrest (height: 45 cm), walk three meters at a comfortable and safe speed, turn around, walk back to the chair, and sit down [31]. The time (in seconds) needed to complete the test was recorded using a stopwatch.

The iTUG variables were collected with a smartphone on the participants' lower back (at the level of the 5th lumbar spine) thru a waist-worn elastic belt. The smartphone-based system was developed within the FARSEEING project [32]. A custom Android application [23] running on the smartphone (Galaxy SIII, Samsung, sampling frequency 100 Hz, accelerometer ± 2g, gyroscope ± 250 ° / s) was used for recording the signals from the triaxial gyroscope and accelerometer embedded within the smartphone [21, 23]. The assessor controlled a second smartphone, which was connected via Bluetooth to the smartphone worn by the participant to start and stop the recording of the iTUG. Inertial signals were processed in MATLAB 2019b (MathWorks, Natick, MA, USA) to identify the four subphases of the TUG (Sit-to-Walk, Walk, 180Turn, and Turn-to-Sit) and to extract a set of instrumented features [23]. The interpretation model according to Coni et al. was used to select the 38 variables from the large number of parameters provided by iTUG [24].

Sensor-based monitoring of mobility performance

The MP parameters were assessed using the triaxial accelerometer "activPAL4™ micro" (PAL Technologies Ltd., Glasgow, Scotland) continuously worn on the central front right thigh for nine consecutive days. The first and last day of the assessment period were excluded and only days with 24 hours measurement were included in the analysis. The instrument is able to derive valid body posture (sitting/lying, standing/upright) and various walking activities (e.g., cadence, steps per day) from raw data [33]. There is no consensus on which variables are most appropriate for different purposes [34]. However, it has been shown that walking duration as a parameter seems to be a surrogate to measure physical activity [35] and it is a well-understood term for communicating with patients [36]. When measuring walking duration, intensity seems to be an important factor, as walking can be performed at different levels from light to brisk [37]. To indicate walking intensity, cadence, as a rate to represent quantified steps displayed over time [38], is an established temporal gait parameter which is strongly ($r=0.94$) and consistently associated with physical activity intensity [39–42]. Therefore, cadence was chosen as the variable for MP in the present study. From the raw data, we calculated the mean cadence (MCA) to represent average MP and the 95th percentile of mean cadence of walks with more than three steps (p95>3stepsMCA) to represent maximum MP.

Statistical Analysis

Normal distribution was tested using the Shapiro-Wilk test. ~~Since the instrumented data were not normally distributed, they were log-transformed using the formal natural logarithm in SPSS.~~ Univariate regressions with MCA and p95>3steps MCA as dependent variables and TUG time as independent variable were calculated to examine the coefficient of determination between TUG time and participants' MP. Since the instrumented data were not normally distributed, they were log-transformed using the formal natural logarithm in SPSS. A stepwise multivariate regression model was used to determine the benefit of the iTUG in terms of reflection of mobility performance. The p95>3stepsMCA was used as the dependent variable, and the instrumented variables according to Coni (2018) (Tab. 5) were used as independent variables. Age, gender, weight, and height were set as control variables for all regression models. All statistical analyses were performed in SPSS (IBM SPSS Statistics, Version 28. An alpha (α) level of 0.05 was used for all statistical tests.

Results

Descriptive Results

A total of 294 participants (sample 1) conducted the TUG and completed the MP measurement. The participants´ mean (SD) age was 78.8 (5.4) and the majority of participants was female (72.8%). The sample on average was cognitively intact (MoCA score [SD] = 26.0 [2.0] points), had a low fear of falling (Short FES-I score [SD] = 10.4 [3.0] points), with 41.2% having a fall event in the past 6 months. The time to complete the TUG (SD) averaged 12.3 (3.4) seconds and the mean cadence (SD) of the participants in everyday life was 65.1 (6.0) steps per minute.

For the multiple regression, only the data from 278 participants (sample 2) could be used, because of incomplete iTUG measurement. The samples did not differ significantly from each other in any participant characteristic (data not shown). Table 1 and table 2 present further participant characteristics and MC and MP parameters of sample 1 and sample 2.

Association between TUG and average vs maximum mobility performance

Table 3 shows the associations between TUG duration and parameters related to average MP (MCA) and maximum MP (p95MCA, p95>3stepsMCA). For MCA a coefficient of determination of $R^2 = .078$ was found. However, TUG duration can explain $R^2=.199$ of the coefficient of determination for p95>3stepsMCA.

Association between iTUG and maximum mobility performance

Multiple stepwise regression showed that iTUG data were more strongly associated with maximum cadence than stopwatch-based TUG time. The strongest model (Tab. 4) showed a coefficient of determination with an adjusted $R^2 = .278$ ($p = .010$) compared to $R^2 = .199$ (TUG, Tab. 3). In addition to the control variables, the model consists of the following variables: *total duration, number of steps, root mean square of vertical acceleration during the turn-to-sit, mean angular velocity of the 180° turn* and *walking duration*. These variables are part of the factors: “walking ability”, “turn-to-sit intensity vertical direction” and “turning ability”, where the factor “walking ability” is reflected with all its variables. The highest beta coefficients were found for the *total number of steps* (b = .646) and the *mean angular velocity of the 180° turn* (b = .385).

Discussion/Conclusion

This study aimed to better understand the association between MC measured by the TUG and MP quantified by sensor-based physical activity monitoring. Results of our first analysis suggest that the TUG better represents *maximum* MP as compared to *average* MP. Results of our second analysis suggest an added value of the iTUG for a more accurate estimation of MP compared to the original TUG.

Association between TUG and average vs maximum mobility performance

Based on previous research in the field of gait assessment, we hypothesised that the TUG would show a greater association with maximum MP compared to average MP. This hypothesis was confirmed by our analysis showing a greater coefficient of determination ($R^2 = .199$) between TUG time and sensor-derived parameters reflecting everyday life maximum MP (i.e., p95>3stepsMCA) as compared to parameters reflecting average MP (MCA, $R^2=.078$). Our results indicate that the TUG provides specific information about a person's ability to carry out maximum performance tasks in the real world. The parameter p95>3stepsMCA reflects those walking episodes with the fastest cadence carried out in everyday life during the one-week sensor-based assessment period. The fact that this parameter explained a higher proportion of the variation of the TUG time suggests that mobility performance measured in the lab is more strongly associated with a person’s ability to carry out daily motor tasks with maximum performance.

Our findings are in line with other recently published studies indicating that the MC-MP relationship differs for average vs. maximum performance. Gordt et al. 2020 found greater correlations (r = 0.31) between MC (gait speed) and MP at higher intensities (>= 3MET) as compared to low intensity activities (<= 3MET) (r=0.15) measured over the course of one week [4]. Like in our study, this demonstrates that MC better reflects a variable representing maximum MP as compared to average MP.

Recently, Wright et al. (2022) found that movement intensity is the most significant parameter of the MC-MP relationship [8], suggesting that studies on the MC-MP relationship can be enhanced with the addition of an intensity measure. Our study demonstrates the validity of this statement and supports the importance of selecting MP variables representing maximum performance in everyday life.

Association between iTUG and average vs maximum mobility performance

We hypothesised that the iTUG would explain a greater coefficient of determination in MP compared to the traditional TUG. This hypothesis was confirmed by our analysis showing a greater coefficient of determination (R^2=.278) between everyday MP (p95>3stepsMCA) and specific iTUG variables as compared to TUG time (R^2 = .199).

We found that three out of the eight additional iTUG factors provided additional information as compared to TUG time only. The iTUG factor “walking ability” represented by the features *total duration, total number of steps* and *walking duration* was most strongly represented in the model. The strong representation of walking can be explained with the fact that our MP measure was also walking-related (cadence in daily life). We found that those who walkied faster during iTUG assessment had a higher MP in daily life. This is in line with Callisaya et al. 2018, who suggest that slower lab-based normal walking speed compared to complex mobility tasks in older people is the strongest predictor of shorter daily distances walked, smaller life space, greater impairment in ADLs, fear of falling, and lower balance confidence [6].

In addition to the “walking ability” factor, we identified two iTUG factors related to turning performance explaining an additional amount of MP variance and increasing the coefficient of determination (i.e., “turn-to-sit intensity vertical direction” and “turning ability”). The highest beta coefficient was found for *mean angular velocity of the 180° turn* feature (b = .385). Our findings suggest that the intensity of the movement increases/decreases with a more confident/cautious approach and that this is reflected in the daily MP. This is perhaps no coincidence, as the importance of the turn velocity for predictive or discriminatory ability has already been recognised in several other studies. Coni et al. 2019 showed that the iTUG features *walk duration* and *turn-to-sit turning maximum velocity* had significant discriminative ability on physical function measured by the Late-Life Function and Disability Instrument in high functioning young seniors [21]. Bergquist et al. 2020 showed that the iTUG was able to predict the Community Balance and Mobility Scale total score with accuracy of 85.2% (84.9-85.5%) in community-dwelling healthy seniors and geriatric patients [22]. Six of the ten features with highest R^2 scores were features obtained from the two turning phases of the iTUG (e.g., *mean velocity first turn, mean velocity turn to sit, peak velocity turn to sit*). The highest R^2 score was found for *mean velocity first turn* and *walk duration* [22]. Caronni et al. 2018 showed that iTUG turning features are the best predictors of balance in neurological patients as measured by the Mini-BEST test [18]. The authors propose *the mean angular velocity during turning* and the *duration of the turn phase* as valid ratio measures of balance [18]. More specifically, we found that a lower turning velocity of the iTUG is associated with a lower daily life MP. Moreover, we found that if turn duration decreases, daily life performance increases.

Strength and limitations

Major strengths of this study are the large sample size, one-week instrumented MP assessment and the systematic approach for classifying iTUG performance based on an established factor concept [24]. Limitations are that our variables of MP measures were restricted to walking performance. Although walking is the most common MP in older adults, we acknowledge that participants may have been engaged in other MP activities (e.g., swimming, cycling) that the sensor-based assessment did not account for. Our sensor-based MP assessment does not reveal information about indoor or outdoor mobility performance. This could be extended in future studies using GPS signals Due to the cross-sectional design of the study, causal inferences cannot be evaluated, and further longitudinal studies are needed to show that changes in challenging MP measures are associated with changes in MC.

Conclusion

Our study highlights that the MC-MP association depends on the specific outcome variables selected for representing MC and MP. Our results show a closer relationship between MC measures and MP measures when using MP measures representing the individuals’ maximum performance. In other words, the MC-MP association becomes more evident if those episodes of daily life MP are selected for analysis that are closer to the performance limit. Such a “testing the limits” paradigm has been described previously in several studies in related research fields [43].

In relation to our second hypothesis, we conclude that the variables collected by the iTUG provide additional information useful for estimating an individual's daily MP. This highlights the need for instrumented MC assessments in older adults and is an important step towards tailored assessments for this target population. Assessment results could form the basis of specific interventions aimed at restoring or improving relevant MC, such as walking and turning ability, which in turn could enable older adults to maintain healthy MP patterns and an active lifestyle.

Statements of Ethics

This study protocol was reviewed and approved by Ethic Review Board of the

Faculty of Behavioral and Cultural Studies at Heidelberg University (document number Schwe2017 2/1–1) and from the Ethic Review Board of the University Hospital and Faculty of Medicine in Tübingen (document number 723/2017BO2). The study is conforming to the respective policy and mandates of the Declaration of Helsinki. Participants' written informed consent is obtained from assessors at their first screening visit at the study site.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

Conceptualization: FK-G, PH and MS; Methodology: FK-G, PH and MS; Data analysis and interpretation: FK-G, AE, PH and MS; Resources: SM; Writing–original draft preparation: PH, AE and MS; Writing–review and editing: CPJ, FK-G, SM, AE, PH and MS. All authors reviewed and critically revised the manuscript for important intellectual content and approved the final manuscript.

Data Availability Statement

All data analysed during this study are included in this article. Further enquiries can be directed to the corresponding author.

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