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Case Report

Evaluation of the Timed Up and Go Test in Patients with Knee Osteoarthritis Using Inertial Sensors

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Abstract: Background: There has been a growing interest in using inertial sensors to explore the temporal aspects of the Timed Up and Go (TUG) test. The current study aimed to analyze the spatiotemporal parameters and phases of the TUG test in patients with knee osteoarthritis (KOA) and compare the results with those of non-arthritic individuals. Methods: This study included 20 patients with KOA and 60 non-arthritic individuals aged 65 to 84 years. All participants performed the TUG test, and 17 spatiotemporal parameters and phase data were collected wirelessly using the BTS G-Walk inertial sensor. Results: Significant mobility impairments were observed in KOA patients, including slower gait speed, impaired sit-to-stand transitions, and reduced turning efficiency. These findings highlight functional deficits in individuals with KOA compared to their non-arthritic counterparts. Conclusions: The results emphasize the need for targeted physiotherapy interventions, such as quadriceps strengthening, balance training, and gait retraining, to address these deficits. However, the study is limited by its small sample size, gender imbalance, and limited validation of the BTS G-Walk device. Future research should include larger, more balanced cohorts, validate sensor reliability, and conduct longitudinal studies. Despite these limitations, the findings align with previous research and underscore the potential of inertial sensors in tailoring rehabilitation strategies and monitoring progress in KOA patients.

Keywords: knee osteoarthritis; timed up and go test; inertial sensors; phase durations; spatiotemporal parameters

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1. Introduction

Annually, approximately one out of every three adults aged 65 and above, and nearly half of individuals over 80, encounter at least one fall [1]. Falls resulting in unintentional injuries are significant contributors to mortality and an increase in their occurrence has been witnessed [2]. The associated non-fatal falls in 2020 were estimated by Medicare to account for $80.0 billion in healthcare costs [3].

On the other hand, osteoarthritis (OA) poses a significant challenge to public health due to its considerable burden on individuals regarding physical and psychosocial impairment [4,5]. Additionally, OA is recognized as one of the most prevalent joint diseases globally [6,7]. In 1990, over 7 million Americans experienced a disability that hindered their ability to engage in essential daily activities [8]. Since that time, the prevalence of the disease, particularly KOA, has experienced a twofold increase [9]. Approximately 18% of women aged 60 years and older are estimated to be affected by the condition, whereas the prevalence among men of the same age group is approximately 10% [6]. The connection between KOA and falls is a topic of debate; however, evidence suggests that gait and balance disorders caused by OA could potentially elevate the risk of falls [10,11].

Thus, specialized screening tools for assessing fall risk are widely recognized as the preferred approach. Among these tools, the TUG test is renowned and considered the gold standard for fall risk assessment, offering numerous advantages [12,13]. The patient gets up from an armchair, goes three meters, turns around, walks back, and sits down again while being watched and timed [14]. It is a simple and easily performed test, making it widely adopted [13,15].

Recently, the TUG test has been conducted using accelerometers worn by patients. This enables a focused analysis of the sit-to-stand and stand-to-sit subtasks, providing valuable information to identify the fall risk in home-based fallers compared to healthy individuals [16]. The study findings indicate that the TUG test successfully identifies 63% of fallers, and when combined with accelerometer data, this percentage increases to 87% in patients equipped with accelerometers [16]. Similarly, a study by Buisseret et al. (2020) demonstrated that using three-dimensional acceleration data from wearable sensors during typical walking can help create a predictive model for the TUG test in older adults. The model showed a narrow margin of error when estimating the TUG scores of the participants. By analyzing the TUG score during regular walking, the model can let clinicians evaluate older persons' fall risks remotely [13].

In addition, instrumented TUG tests can yield valuable information regarding the kinematics of functional tasks, such as accelerations and angular velocities [17,18]. However, there remain several unresolved issues in the scientific literature. The timing and transitions between different test phases hold crucial clinical information for diagnosis and prognosis [19]. Accurately analyzing these times is, therefore, of fundamental importance.

Consequently, it is not surprising that interest in using inertial sensors to investigate the temporal information of the TUG test has considerably grown [20–24]. Thus, this study aimed to analyze the spatiotemporal parameters and phases of the TUG test using inertial sensors in patients with pre-operative KOA and compare the results with those of healthy individuals.

2. Materials and Methods

2.1. Participants

In the current study, 20 patients with primary KOA (5 males and 15 females) with a mean age of 74.84 (6.694) years (65 to 88 years) and 60 non-arthritic controls (15 males and 45 females) with a mean age of 72.25 (5.220) years (65 to 88 years) were included. Cases and controls were individually matched on age, sex, and the bone mass index (BMI). Each case with KOA was matched with 3 controls. Patients diagnosed with end-stage unilateral primary KOA scheduled for a total knee arthroplasty (TKA) were recruited. The inclusion criteria required patients to have the ability to walk independently without the need for ambulatory aids. The exclusion criteria encompassed patients with neurological, cardiorespiratory, or other severe orthopedic conditions leading to ambulatory impairment and a lack of individual, independent mobility. The controls were healthy individuals who had no history of orthopedic or neurological disorders, including recent injuries, surgeries, or pharmaceutical therapy that may have affected their gait and balance.

Prior to participation, all individuals provided written consent after receiving a detailed explanation of the study's objectives. The study protocol received approval from the IRB Committee of the School of Physical Education and Sport Science, National and Kapodistrian University of Athens, Greece (Approval Number: 1306/22 September 2021).

2.2. Instrumentation

A wireless inertial sensor (G-Walk, BTS Bioengineering S.p.A., Milan, Italy) was used to collected TUG test data. The device is equipped with 4 IMUs (Inertial Measurement Units). Each IMU is equipped with a three-axis accelerometer, magnetometer, gyroscope, and positioning system receiver. Specifically, it features a triaxial accelerometer (16-bit/axis) with multiple sensitivity options, offering a dynamic range of ±2, ±4, ±8, and ±16 g and a bandwidth ranging from 4 to 1000 Hz. Additionally, it includes triaxial magnetometers (13-bit) with a dynamic range of ±1200µT and a bandwidth of up to 100 Hz and a triaxial gyroscope (16-bit/axis) with multiple sensitivity options, providing a dynamic range of ±250, ±500, ±1000, and ±2000°/sec and a bandwidth ranging from 4 to 8000 Hz. The device is equipped with a GPS receiver with a position accuracy of 2.5 m up to 5 Hz or 3 m up to 10 Hz and a bandwidth of up to 10 Hz.

The module's dimensions are 70 mm L × 40 mm W × 18 mm H (2.75 in L × 1.57 in W × 0.7 in H), and it supports an acquisition frequency of up to 1000 Hz. The module connects to a laptop for data acquisition via Bluetooth 3.0 (class 1.5), providing a range of up to 60 m in the line of sight.

2.3. Acquisition Protocol

The sensor was positioned inside a semi-elastic black belt, which was placed above the iliac wings at the level of the L4 vertebra in all individuals undergoing the TUG test, as illustrated in Figure 1.

Figure 1. The G-walk inertial sensor device was placed in a pocket of a semi-elastic belt positioned above the iliac wings, at the level of the L4 lumbar vertebra.

All participants were instructed how to perform the TUG test to enhance the reliability of the test results. The participants were seated with their backs against the backrest and their arms resting on the chair's armrests. Upon receiving the signal from the operator to start, participants were required to stand, walk three meters ahead in a straight line, turn without changing positions, and then return to the chair and sit down again.

Using Bluetooth technology, gait data were captured and transmitted to a computer, where the dedicated G-Studio software (Version 1.3.0) processed the collected data and calculated various spatiotemporal parameters. The reported exam window is depicted in Figure 2.

Analysis Report - Timed Up and Go

Parameters	Value	Units
Analysis Duration	13.33	s
Functional mobility skill	Independent	

Parameters	Sit to Stand	Stand to Sit	Units
Phase Duration	1.70	1.90	s
Antero-Posterior Acceleration	7.2	4.6	m/s²
Lateral Acceleration	2.2	3.4	m/s²
Vertical Acceleration	6.2	4.0	m/s²
Parameters	Mid Turning	End Turning	Units
Phase Duration	1.90	2.96	s
Maximum Rotation Speed	137.1	161.0	°/s
Average Rotation Speed	76.5	60.3	°/s

Figure 2. The report of the TUG test, as is provided by the dedicated G-Studio software.

2.4. Data Analysis

The G-studio software extracted various spatiotemporal parameters, including the following:

Analysis Duration, s: This parameter represented the overall duration of the entire trial.

For the Sit-to-Stand and Stand-to-Sit test phases, the following parameters were calculated:

- Phase Duration, s: Indicated the average time interval for each movement in the respective phase.
- Antero-Posterior Acceleration, m/s^2: Represented the average range of the antero-posterior acceleration achieved during each assessed phase.
- Lateral Acceleration, m/s^2: Denoted the average range of medial–lateral acceleration observed during each assessed phase.
- Vertical Acceleration, m/s^2: Captured the range of vertical acceleration experienced during each assessed phase.
- Parameters were generated for the Mid Turning and End Turning sections:
- Phase Duration, sec: Represented the average temporal duration of each turn in the test.
- Maximum Rotation Speed, °/s: Indicated the maximum speed reached during each turn.
- Average Rotation Speed, °/s: Represented the average speed maintained throughout each turn.

Lastly, the report section included information on the test phases, documenting the duration of each phase (e.g., Sit to Stand (rising), Forward Gait (walking forward), Return Gait (walking back), Mid Turning (intermediate rotation), End Turning (final rotation), and Stand to Sit (sitting)) recorded during the trial (refer to the example in Figure 3 for further clarity).

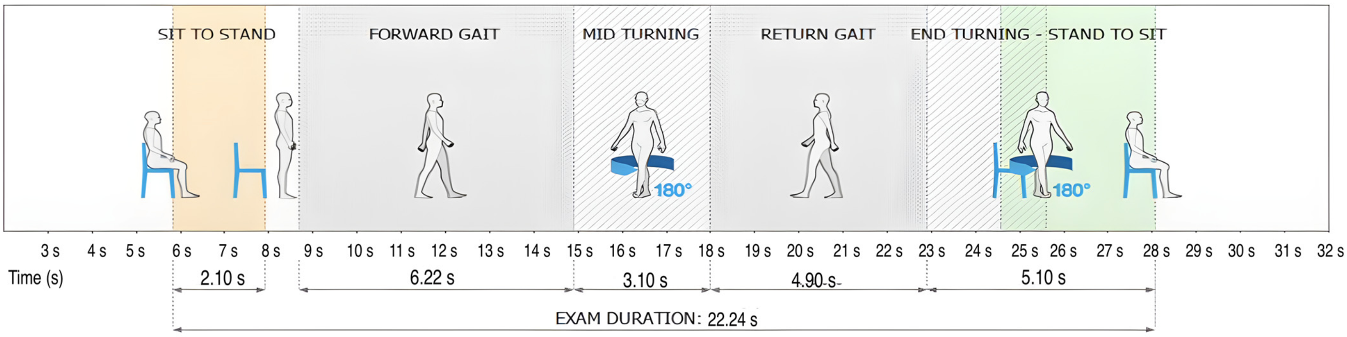

Figure 3. The G-Studio software provides a graphic representation of the various phases of the TUG test.

2.5. Statistical Analysis

All analyses were conducted using the statistical package IBM SPSS, version 28.00 (IBM Corporation, Somers, NY, USA). Data were expressed as the mean ± the standard deviation or the median (IQR) in the case of a violation of normality. Additionally, the Kolmogorov–Smirnov and Shapiro–Wilks tests examined the normal distribution of the parameters. The independent sample *t*-test and Fisher's exact test also examined the homogeneity between the compared groups. Moreover, the independent sample *t*-test or Mann–Whitney test was performed comparing the parameters between the groups in the case of a violation of normality. Finally, all tests were two-sided, and the statistical significance was set at $p < 0.05$.

3. Results

During the data analysis, 17 TUG test spatiotemporal parameters and phase data were obtained from 20 OA and 60 healthy individuals. Table 1 displays the demographic statistics and highlights the homogeneity between the compared groups for all demographic variables ($p > 0.05$).

Table 1. Demographic data of the patients included in the study presented as the mean and standard deviation (SD).

	All Participants (n = 39)		
	Knee Osteoarthritis Patients (n = 20)	**Healthy Controls (n = 60)**	***p*-Value**
Age (years)	74.84 (6.694)	72.25 (5.220)	0.184
Weight (kg)	83.79 (16.788)	78.60 (9.816)	0.243
Height (cm)	165.74 (7.117)	165.00 (8.784)	0.776
BMI	30.46 (5.61)	29.00 (3.83)	0.335
Shoe Size (EU)	39.68 (2.358)	39.55 (2.502)	0.864
Gender, Male/Female, N (%)	5 (15.8)/15 (84.2)	15 (25.0)/45 (75.0)	0.695

Additionally, Table 2 presents significant differences between the OA patients' and healthy individuals' TUG test results. Particularly, the group of OA patients had statistically higher values of the Analysis Duration ($p < 0.001$), Sit-to-Stand Phase Duration ($p < 0.001$), Stand-to-Sit Phase Duration ($p = 0.017$), Forward Gait Phase Duration ($p < 0.001$), Return Gait Phase Duration ($p < 0.001$), Mid Turning Phase Duration ($p < 0.001$), and End Turning Phase Duration ($p < 0.001$) and lower values of the Sit-to-Stand Antero-Posterior Acceleration ($p = 0.002$), Sit-to-Stand Lateral Acceleration ($p = 0.002$), Sit-to-Stand Vertical Acceleration ($p < 0.001$), Mid Turning Maximum Rotation Speed ($p = 0.002$), End Turning Maximum Rotation Speed ($p < 0.001$), Mid Turning Average Rotation Speed ($p < 0.001$), and End

Turning Average Rotation Speed ($p < 0.001$) compared to healthy individuals. Nonetheless, three parameters, the Stand-to-Sit Antero-Posterior Acceleration ($p = 0.060$), Stand-to-Sit Lateral Acceleration ($p = 0.086$), and Stand-to-Sit Vertical Acceleration ($p = 0.156$), had no significant differences.

Table 2. Parameter analysis presented as mean and standard deviation (SD).

	Knee Osteoarthritis Patients	Healthy Controls	*p*-Value
Analysis Duration, s	22.32 ± 5.49	12.94 ± 1.88	<0.001
Sit-to-Stand Phase Duration, s	2.35 ± 0.64	1.62 ± 0.33	<0.001
Forward Gait Phase Duration, s	5.65 ± 2.45	2.96 ± 0.83	<0.001
Return Gait Phase Duration, s	5.58 ± 2.46	3.03 ± 0.72	<0.001
Stand-to-Sit Antero-Posterior Acceleration, m/s^2	3.07 ± 1.64	4.06 ± 1.53	0.060
Sit-to-Stand Vertical Acceleration, m/s^2	2.83 ± 1.01	4.02 ± 1.07	<0.001
Stand-to-Sit Vertical Acceleration, m/s^2	4.95 ± 2.70	6.17 ± 2.57	0.156
End Turning Phase Duration, sec	3.35 ± 0.92	1.84 ± 0.56	<0.001
Mid Turning Maximum Rotation Speed, °/s	116.70 ± 33.78	149.60 ± 27.83	0.002
End Turning Maximum Rotation Speed, °/s	106.14 ± 29.27	168.02 ± 35.48	<0.001
Mid Turning Average Rotation Speed, °/s	56.94 ± 20.12	88.29 ± 20.48	<0.001
End Turning Average Rotation Speed, °/s	50.59 ± 14.95	91.29 ± 22.76	<0.001
	Median (IQR)	**Median (IQR)**	
Stand-to-Sit Phase Duration, s	2.30 ± 0.90	1.90 ± 0.75	0.017
Sit-to-Stand Antero-Posterior Acceleration, m/s^2	2.00 ± 1.20	3.10 ± 0.92	0.002
Sit-to-Stand Lateral Acceleration, m/s^2	1.40 ± 0.60	1.70 ± 0.38	0.002
Stand-to-Sit Lateral Acceleration, m/s^2	3.10 ± 1.50	3.65 ± 0.92	0.086
Mid Turning Phase Duration, s	3.03 ± 1.20	1.88 ± 0.80	<0.001

4. Discussion

The primary aim of this study was to use inertial sensors on patients with pre-operative KOA to analyze the spatiotemporal parameters and phases of the TUG test. Consequently, the findings from this study provide a comprehensive approach to quantifying 17 spatiotemporal parameters and phases of the TUG test, offering objective measurements that reduce subjectivity and potential bias in functional assessments. These objective data are crucial for evaluating mobility and functional performance in KOA patients, particularly in areas such as gait acceleration, sit-to-stand transitions, and turning efficiency during the TUG test.

This study also revealed significant differences in the TUG test performance between individuals aged 65 and older with KOA and their healthy counterparts. KOA patients exhibited longer TUG completion times, which aligns with previous studies [25–27], confirming that KOA patients tend to exhibit slower completion times compared to healthy individuals. This finding emphasizes the sensitivity of the TUG test in detecting mobility impairments and highlights its value in assessing KOA severity. In line with the work of Khalaj et al. (2014), who showed significant variations in TUG times between mild and moderate KOA patients, these results further validate the TUG test as a reliable tool for assessing the severity of KOA [27].

Additionally, the study reinforces the relevance of the 30 s chair stand test, which is often linked with TUG test performance and is a key component of functional mobility. Jones et al. (2013) demonstrated its value in assessing lower body strength, and the findings indicated that KOA patients, due to quadriceps weakness, face difficulties in performing the sit-to-stand transition, which prolongs their TUG completion time [26]. This observation underscores the need for strength-based interventions in KOA rehabilitation to improve functional mobility.

Significant differences were also found in 14 out of the 17 spatiotemporal parameters measured, providing clinicians, including physiotherapists, with valuable tools to assess the KOA severity and tailor treatment plans. Quadriceps weakness, a hallmark of KOA [28], impairs key TUG test phases such as sit-to-stand and turning, directly contributing to prolonged test times. This highlights the importance of strength-focused rehabilitation to improve functional mobility in KOA patients [29].

Furthermore, pain and joint stiffness commonly associated with OA can lead to compensatory movements that alter spatiotemporal parameters and impair normal gait patterns [30]. As noted by Metcalfe et al. (2013), these changes in movement patterns often lead to shorter steps, slower gait speeds, and longer stance phases during walking, all of which were observed in this study [31].

Interestingly, the findings are consistent with studies conducted in other patient populations. For example, Na et al. (2016) examined the center-of-mass acceleration during sit-to-stand motions in stroke patients, revealing similar altered acceleration patterns during functional movements [32]. Similarly, Manckoundia et al. (2006) compared motor strategies in individuals with Alzheimer's disease and elderly controls, showing similar acceleration patterns during sit-to-stand transitions [33]. The parallels between KOA and other patient groups, such as those with Parkinson's or Alzheimer's disease, highlight the potential of the TUG test as a universal tool for assessing fall risk across various clinical contexts. It is important to note that all these patient populations—KOA, Parkinson's, and Alzheimer's—are at a higher risk for falls [25,34,35], which the TUG test's performance can effectively capture.

Moreover, the variability in deterioration patterns among KOA patients emphasizes the need for individualized assessment. While KOA patients may experience common functional impairments, each patient's functional decline may follow a unique pattern, which affects their mobility and performance during the TUG test [27]. Using inertial sensors to identify these individual patterns can help physiotherapists tailor rehabilitation efforts to address specific deficiencies, such as balance or gait issues, that are critical during different phases of the TUG test [36]. Sibley et al. (2011) noted that quantitative data from the TUG test could assist in the creation of customized rehabilitation plans [37].

Finally, the use of inertial sensors in this study enabled the continuous monitoring of spatiotemporal parameters over time and will allow physiotherapists to track changes in mobility and assess the effectiveness of interventions. Shumway-Cook et al. (2000) emphasized the importance of detecting subtle declines in mobility, especially for older adults or those with mobility impairments, to allow for timely interventions [38]. By incorporating detailed spatiotemporal data from the TUG test, physiotherapists can better adjust treatment strategies to optimize outcomes for KOA patients and improve their overall quality of life, as demonstrated by Wu et al. (2022) [39].

5. Limitations

It is important to acknowledge several limitations of this study. Firstly, a significant limitation is the observed imbalance in the distribution of sexes within the sample. A noticeable disparity existed in the gender composition between the group of OA patients and the age-matched healthy individuals. This gender difference might have introduced potential biases and confounding factors, impacting the generalizability and interpretation of our findings. This disparity reflects the higher prevalence of OA among females [40]. Future studies should address this issue through stratified sampling, larger sample sizes, and statistical adjustments for gender-related biases.

Secondly, the use of a small convenience sample, necessitated by time and resource constraints, limits the representativeness of the findings. This sampling method may have introduced selection bias, as participants were self-selected or readily accessible. Despite these limitations, a post hoc power analysis revealed a statistical power of 100% for the between-group comparison. Future research should aim for larger, randomized cohorts to enhance generalizability.

Furthermore, a significant limitation is the absence of reliable studies in the literature that thoroughly investigate the validity and reliability of the BTS G-Walk in capturing acceleration and angular velocity data during the TUG test. While some studies demonstrate the reliability and validity of gait spatiotemporal parameters with the BTS G-Walk wearable sensor [41,42], only one study assessing the TUG test was identified [21], which did not meet the criteria. Further research is needed to assess the device's accuracy and reliability in this context.

Finally, the cross-sectional design of this study limits its ability to evaluate temporal changes in the TUG test parameters. Longitudinal studies are required to assess mobility changes and the effectiveness of interventions over time for KOA patients.

6. Conclusions

This study analyzed 17 spatiotemporal parameters of the TUG test using inertial sensors to objectively assess functional performance in pre-operative KOA patients. The findings revealed significant mobility impairments, including a slower gait speed, impaired sit-to-stand transitions, and a reduced turning efficiency, compared to healthy individuals. These results underscore the value of inertial sensors in identifying specific functional deficits, enabling physiotherapists to design targeted interventions such as quadriceps strength training, balance exercises, and gait training. Functional movement exercises for sit-to-stand and turning transitions, combined with sensor-based monitoring, can support tailored rehabilitation plans and timely adjustments to improve patient outcomes.

While the study's gender imbalance and convenience sampling limit generalizability, the observed differences remain clinically meaningful, supported by robust statistical power. Future studies should aim for a more balanced gender distribution, larger sample sizes, and longitudinal designs to assess temporal changes and intervention effectiveness. Additionally, further research is needed to validate the reliability of the BTS G-Walk device in this context to strengthen the methodological foundation for future applications.

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Informed Consent Statement: All participants provided written informed consent after being informed of the study's purpose.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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