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Spatio-temporal gait parameters derived from low-cost IMUs for frailty assessment in older adults: a cross-sectional study in Honduras

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Abstract*—Population aging represents an increasing challenge for healthcare systems and society as a whole. This phenomenon is particularly relevant in low- and middle-income countries, where access to objective and scalable tools for functional assessment remains limited or nonexistent. Frailty in older adults is commonly assessed through clinical physical performance tests such as the Short Physical Performance Battery (SPPB). However, these evaluations rely on observer-based scoring, which may limit the detection of subtle changes in functional performance. This study proposes the instrumentation of the SPPB using low-cost inertial measurement units (IMUs) to obtain objective gait and balance metrics. A cross-sectional observational study was conducted with 30 participants (mean age: 72.4 ± 6.8 years). Three portable IMUs were placed at the waist and both ankles during the execution of the SPPB subtests. Data processing included filtering, event-based segmentation, and parameter extraction. The analyzed metrics included gait speed, cadence, and balance variability, estimated through root mean square (RMS) acceleration along the antero-posterior and mediolateral axes. Additionally, a temporal slope index was incorporated, calculated from the difference between the duration of the last and first repetitions of the chair-stand test and normalized by the number of intervals. The median gait speed was 0.437 m/s (IQR: 0.381–0.502). Participants with poorer performance exhibited lower gait speed and higher cadence, suggesting compensatory strategies. These results demonstrate the feasibility of the proposed approach for extracting spatiotemporal gait parameters from low-cost IMUs as an objective support tool for frailty assessment in older adults.

***Keywords*– frailty, gait analysis, low-cost inertial sensors, older adults, Short Physical Performance Battery (SPPB)**

I. INTRODUCTION

Global population ageing represents one of the most significant challenges of the present century, with direct implications for health, functional capacity, and quality of life among older adults [1]. It is estimated that by 2030, one in six people worldwide will be aged 60 years or older, and that by 2050, nearly 80% of the older population will reside in low- and middle-income countries [2].

Honduras is part of this demographic context, where older adults account for approximately 14% of the national population. This group is characterized by pronounced territorial inequalities as well as educational and economic limitations [3]. Reports indicate that nearly 75% of the population lives in poverty, 77% earns less than the cost of the basic food basket, and approximately 90% of older adults remain economically active due to the lack of pension or retirement benefits [4].

In response to this scenario, international organizations have promoted initiatives aimed at improving the well-being of older populations, among which the Decade of Healthy Ageing (2021–2030) stands out [5]. Within this framework, the World Health Organization defines healthy ageing as "the process of developing and maintaining the functional ability that enables well-being in older age" [6]. This concept extends beyond the absence of disease by incorporating physical, mental, and social well-being [7], with a particular emphasis on independence and functional capacity [8].

Frailty is a multifaceted concept that has evolved from an exclusively physical perspective toward a broader framework that integrates psychological and social dimensions [9]. It is defined as a geriatric syndrome with an estimated prevalence ranging from 5% to 17% among older adults [10]. The most widely accepted model, proposed by Fried et al. [11], characterizes physical frailty based on five criteria: unintentional weight loss, exhaustion, low physical activity, slow gait speed, and muscle weakness [12].

Given its abstract nature, frailty cannot be directly measured; instead, its assessment relies on functional indicators and statistical associations between observable variables [13]. Importantly, although frailty was initially considered an irreversible condition, growing evidence suggests that it can be reduced or even reversed through appropriate interventions [14]–[17].

Among older adults, frailty is commonly associated with functional impairments that manifest as gait instability [18]. Consequently, gait parameters have been widely adopted as functional indicators of frailty. Gait speed, in particular, has emerged as a relevant predictor of physical function and adverse outcomes [19], including falls and functional decline [20]. In this context, inertial measurement units (IMUs) have proven to be valuable tools for the objective characterization of gait, enabling the analysis of spatiotemporal parameters and contributing to a more comprehensive assessment of locomotor performance [21].

One of the most commonly used tools for functional assessment and frailty identification is the Short Physical Performance Battery (SPPB), which evaluates balance, gait speed, and the ability to rise from a chair [22]. The SPPB has demonstrated reliability and validity for frailty detection, prediction of geriatric syndromes [23], and monitoring of functional status over time [24]. However, discrepancies may arise between performance observed during supervised assessments and functional performance in daily life [25]. Moreover, the requirement for professional supervision limits its applicability in certain settings and patient profiles [26], [27].

The instrumentation of the SPPB using IMUs has been shown to improve the precision of gait parameter measurements [20], facilitate assessments by increasing autonomy and reliability [26], and contribute to fall risk prediction [18].

Nevertheless, data accuracy depends on factors such as sensor type and placement [28]. In addition, more complex systems tend to be costly and are not always accessible in resource-limited environments [29]. Sensor recordings may also be affected by noise resulting from external movements or errors in initial sensor orientation [30].

In this context, the present study proposes the instrumentation of the SPPB using low-cost IMUs to objectively assess spatiotemporal gait parameters associated with frailty in older adults. This approach prioritizes an accessible and replicable data acquisition scheme, aimed at integration into routine functional assessments in resource-limited settings. From a preventive perspective, this methodology is expected to contribute to the early detection of functional decline and to support the preservation of independence and quality of life among the older adult population in Honduras.

II. Methodology

An observational, cross-sectional, and quantitative study was conducted with the aim of instrumenting SPPB using IMUs in older adults. The study focused on the characterization of gait-related parameters obtained during the execution of standardized functional tasks. All procedures were carried out in accordance with the principles of the Declaration of Helsinki, and written informed consent was obtained from all participants prior to data collection.

A. Participants

With the aim of developing technologies for the assessment of frailty and physical functionality in older adults, this population was defined as the target group of the study. Specific inclusion and exclusion criteria were established accordingly. Participants aged 60 years or older were included if they were able to ambulate independently or with the use of mobility aids and met at least one criterion of the Fried frailty phenotype. Individuals who did not provide written informed consent, who presented difficulties in understanding the study protocol—as verified through a simple interaction test with the device—or who were deemed clinically unstable by the responsible investigator were excluded from the study.

Participant recruitment was conducted at the Puerto Cortés health center, as well as through relatives, neighbors, and acquaintances of the researchers, following a convenience sampling approach. In addition, basic demographic and contextual information was collected using a brief non-standardized questionnaire. The information gathered was used to characterize the general context of the participants.

B. Apparatus

Data acquisition was performed using three six-degree-of-freedom 6-DoF IMUs implemented with the MPU6050 sensor.

The sensor integrates a triaxial accelerometer and a triaxial gyroscope. An ESP32-WROOM-S3 microcontroller was used for data acquisition, system control, and data transmission management. Linear acceleration and angular velocity along the X, Y, and Z axes were measured at a constant sampling frequency of 50 Hz. Communication between the sensor and the microcontroller was established via the I^{2}C protocol.

TABLE I
Device Cost Breakdown

Component	Cost (USD)
ESP32-WROOM-S3 microcontroller	17.01
MPU6050 inertial sensor (6-DoF)	3.50
PCB / protoboard and assembly	2.00
Cables and connectors	1.50
Portable power bank	9.45
3D-printed enclosure (102.5 g)	5.81
Body fixation (elastic band / Velcro)	2.00
Total cost per device	**41.27**

The estimated cost per device was approximately USD 41.27, based on the acquisition prices of the electronic components and fabrication materials, as summarized in Table I. The system was designed to be portable, allowing wireless data transmission to an external device for storage and visualization during the assessment sessions.

(a) Front view (b) Rear view (c) Side view

Fig. 1. Placement of the IMU sensors on the participant.

C. Data Acquisition

Inertial signals were recorded during the execution of the SPPB in a single session per participant. Data acquisition was performed continuously while participants completed the balance, gait speed, and chair stand subtests, following the standardized SPPB protocol. The three IMUs were placed at predefined body locations and remained consistent across all participants to ensure data consistency between subjects and test conditions. The sensor configuration is illustrated in Figure 1. Prior to the execution of the functional tests, basic contextual information was collected using a brief questionnaire.

The assessment began with the balance test, which included three consecutive standing positions, as shown in Figure 2: (a) feet together, (b) semi-tandem stance, and (c) tandem stance. Each position was maintained for 10 seconds in accordance with the established protocol. The start and end of each position were defined to enable subsequent signal segmentation.

(a) Side-by-side-stand (b) Semi-Tandem Stand (c) Tandem Stand

Fig. 2. Balance test conditions during the SPPB protocol.

The walking speed test was performed over a distance of 4 m, covered at a normal pace, Figure 3. The execution time was recorded from the start of the movement until completion of the established route. Subsequently, the chair stand test was performed, asking participants to perform the movement as quickly as possible, while maintaining the corresponding safety measures, Figure 4.

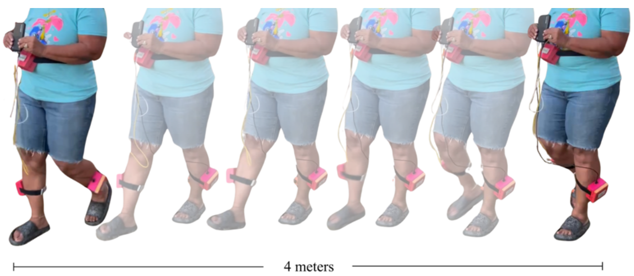

Fig. 3. Gait speed test over a 4-meter walking distance during the SPPB protocol.

Each SPPB subtest was evaluated according to the standardized SPPB scoring system. Gait speed and chair stand performance were assessed manually using a stopwatch, while balance performance was scored based on the participant's ability to maintain each standing position for the required duration. The total score ranged from 0 to 12 points. Throughout the session, a control interface was used to select and label each subtest, helping preserve data organization for later segmentation and processing.

Fig. 4. Sequence of movements during the chair stand subtest of the SPPB.

D. Data Processing

1) Processing: Inertial signals were preprocessed using the same procedure for all sensors in order to reduce noise while preserving motion-related components relevant to human movement.

A fourth-order low-pass Butterworth filter was applied, with a cutoff frequency of 6 Hz and a sampling frequency of 50 Hz. The cutoff frequency was normalized with respect to the Nyquist frequency (fs/2), and filtering was implemented using a zero-phase scheme through the filtfilt function to avoid temporal distortions in the signal. This procedure attenuated high-frequency components associated with noise and vibrations ($>$ 6 Hz) while preserving the spectral content relevant to gait and other functional movements (approximately 0.5–3 Hz). Figure 5 presents a representative example of the filtering effect on the acceleration signal along the x-axis of the waist-mounted sensor during the gait test.

2) Segmentation: Gait events were identified from waist-mounted inertial signals using a combination of angular velocity and linear acceleration. Specifically, the gyroscope signal along the vertical axis (z-axis) and the accelerometer signal along the anteroposterior axis (x-axis) were selected due to their sensitivity to lower-limb rotational motion and foot–ground interaction during walking.

Initial Contact (IC) events were detected from characteristic peaks in the acceleration signal associated with foot strike, while Toe-Off (TO) events were identified from local extrema in the gyroscope signal corresponding to the transition from stance to swing. The temporal succession of IC and TO events enabled segmentation of each gait cycle into stance and swing phases, allowing a consistent delineation of consecutive gait cycles (Fig. 6).

This event-based segmentation provided a reliable temporal framework for subsequent analyses and enabled the extraction of spatiotemporal gait parameters, including gait speed, cadence, step timing, and cycle-level variability.

3) Parameters: The extracted parameters included gait speed, cadence, and walking duration during the 4-m walk task; directional postural sway quantified as RMS acceleration in the anteroposterior and mediolateral axes during balance; and chair stand performance metrics, including total execution time and repetition-level duration slope.

Gait-related parameters were derived from the temporal characteristics of the walking task.

Gait speed was computed as the ratio between the walked distance and the execution time, while cadence was estimated as the number of detected steps normalized by the walking duration and expressed in steps per minute.

Postural stability during the balance task was characterized through acceleration variability. Directional postural sway was quantified as the root mean square (RMS) of the acceleration signal in both the anteroposterior and mediolateral axes, defined as:

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} a_i^2} \tag{1}$$

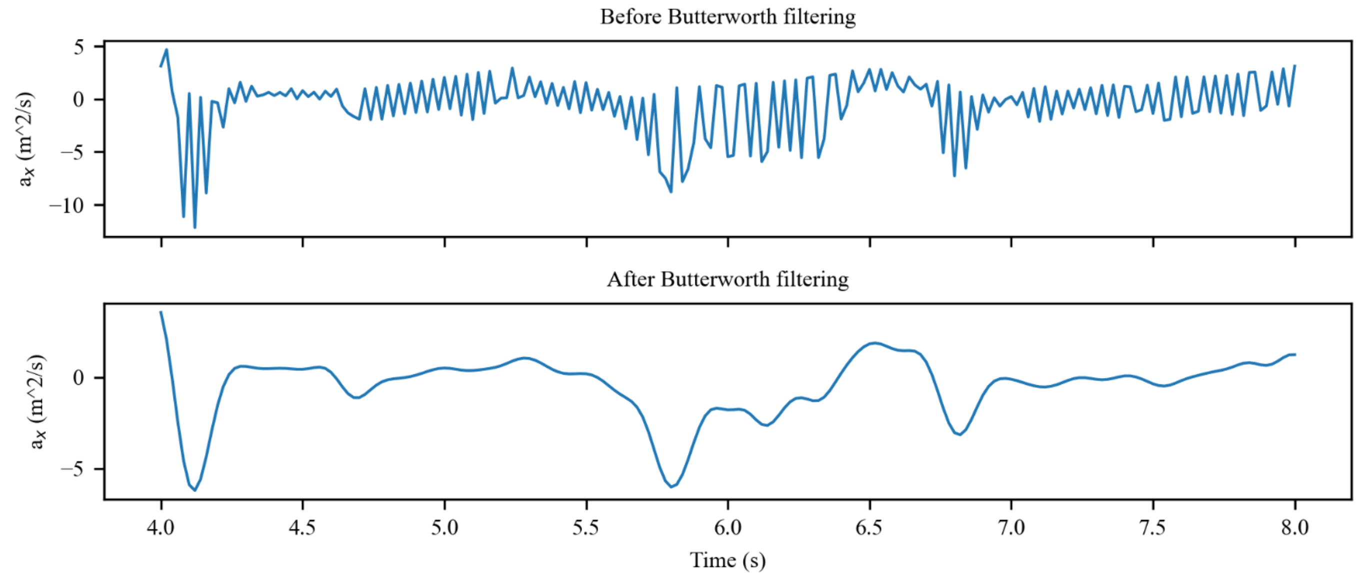

Fig. 5. Example of the X-axis acceleration signal before and after applying a Butterworth low-pass filter.

where a_i represents the acceleration sample and N denotes the total number of samples within the analyzed interval.

Lower-limb function during the chair stand task was described using the total execution time and a repetition-level duration slope. The slope was computed as:

$$\text{slope} = \frac{T_{\text{rep5}} - T_{\text{rep1}}}{4} \tag{2}$$

This metric summarizes performance changes across repetitions, providing insight into adaptation or fatigue during repeated sit-to-stand movements.

III. Results

A. Study population characteristics

The study included 30 older adults with a mean age of 72.4 $\pm$ 6.8 years. Women represented 60.0% of the sample. With respect to living conditions, 30.0% of participants reported living alone, and most were under regular medication (70.0%), reflecting a high prevalence of chronic conditions within the cohort.

A history of two or more falls during the previous year was reported by 23.3% of participants, indicating an increased risk of mobility-related impairments. Additionally, 20.0% had a prior diagnosis of cognitive impairment, which may influence both motor performance and task execution during functional assessments. Overall, the sample exhibits heterogeneous demographic and clinical characteristics commonly observed in older adult populations assessed in clinical and community settings.

A detailed summary of the demographic and clinical characteristics of the study population, including age distribution, sex, and relevant medical background, is presented in Table II.

TABLE II
POPULATION CHARACTERISTICS

Variable	Value
Participants (n)	30
Age (years), mean $\pm$ SD	72.4 $\pm$ 6.8
Female, n (%)	18 (60.0%)
Living alone, n (%)	9 (30.0%)
Under medication, n (%)	21 (70.0%)
$\geq$2 falls in last year, n (%)	7 (23.3%)
Cognitive impairment diagnosed, n (%)	6 (20.0%)

IMU-based analysis of the SPPB walking task is summarized in Table III. After excluding eight participants with walk segmentation failures, valid gait data were obtained from 23 participants. The cohort exhibited a median gait speed of 0.437 m/s (IQR: 0.381–0.502), accompanied by a median 4-m walk duration of 9.15 s (IQR: 7.98–10.51) and a median cadence of 63.2 steps/min (IQR: 59.7–70.1). Together, these values reflect a slow locomotor pace and reduced step length, consistent with the gait patterns typically reported in frailty and with the SPPB walking scores observed in this cohort.

TABLE III
IMU-DERIVED FUNCTIONAL PERFORMANCE METRICS

Outcome measure	Median [IQR]
Gait speed (m/s)	0.437 [0.381, 0.502]
4-m walk duration (s)	9.15 [7.98, 10.51]
Cadence (steps/min)	63.2 [59.7, 70.1]
Balance RMS – mediolateral (m/s^2)	2.331 [1.006, 3.566]
Balance RMS – anteroposterior (m/s^2)	1.253 [0.767, 1.603]
Chair stand total time (s)	16.86 [12.83, 19.59]
Chair stand duration slope (s/rep)	−0.116 [−0.290, −0.055]

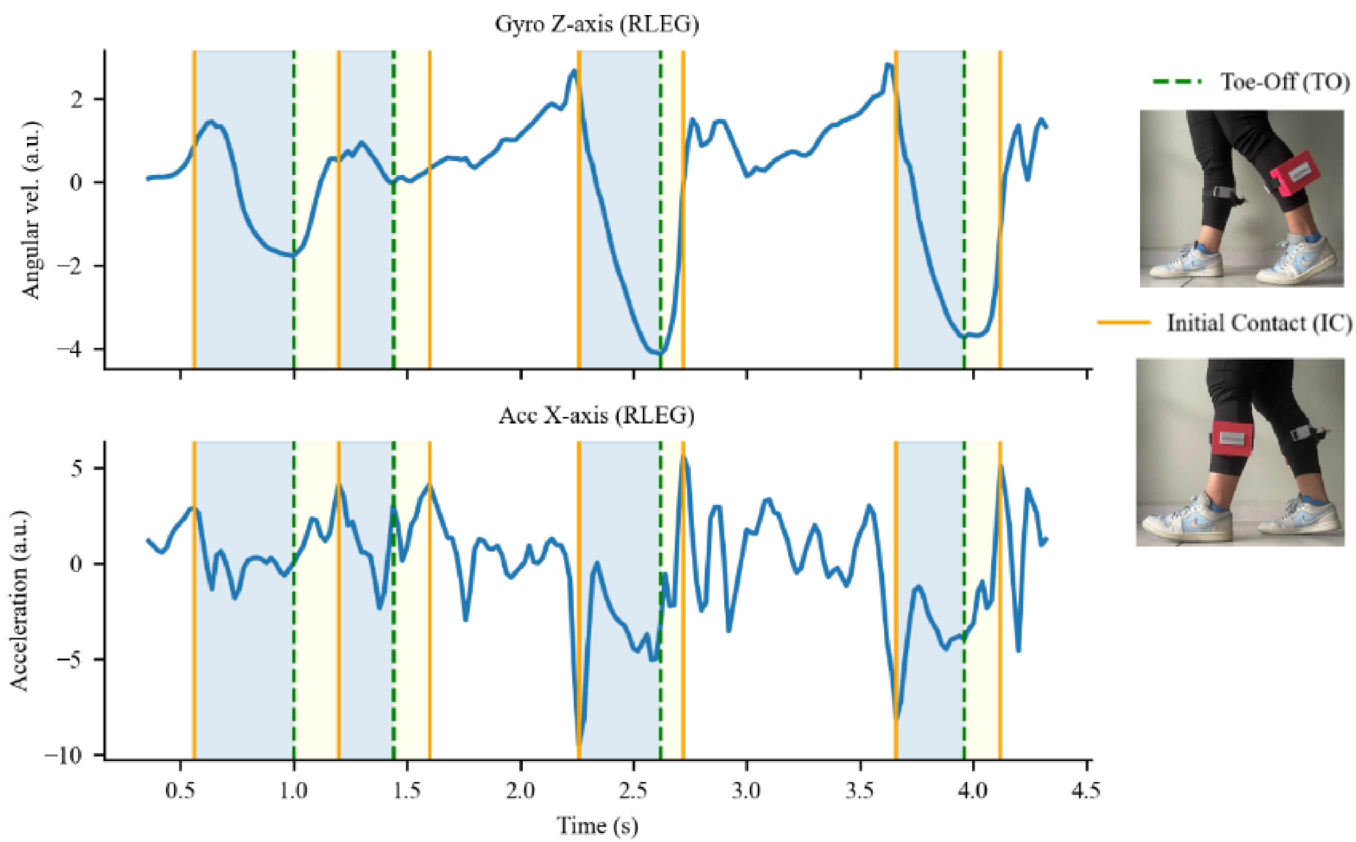

Fig. 6. Detection of gait events using IMU signals from the right lower extremity (RLEG), showing initial contact (IC) and toe-off (TO) identified from the gyroscope Z-axis and accelerometer X-axis signals.

Instrumented metrics derived from waist-mounted inertial sensors during the SPPB tests in older adults ($n = 23$). Values are reported as median and interquartile range (IQR).

Balance-related metrics revealed higher variability in the mediolateral direction, with a median RMS acceleration of 2.331 m/s² (IQR: 1.006–3.566), compared to the anteroposterior direction, which exhibited a median RMS of 1.253 m/s² (IQR: 0.767–1.603).

Regarding the chair stand task, the total execution time presented a median of 16.86 s (IQR: 12.83–19.59). Additionally, the chair stand duration slope showed a negative median value (-0.116 s/rep, IQR: -0.290 to -0.055), indicating a progressive reduction in performance over successive repetitions.

TABLE IV
CLINICAL WALK CATEGORIES AND IMU-DERIVED METRICS

Clinical walk category (SPPB)	**n**	**Gait speed (m/s)**	**Cadence (steps/min)**
6.21–8.70 s (2 points)	21	0.506 ± 0.087	69.24 ± 6.62
$>$ 8.70 s (1 point)	9	0.466 ± 0.040	72.05 ± 6.75
SPPB classification by stopwatch time (n = 30); IMU metrics from valid segmentations (n = 16 and n = 7, respectively).			

Clinical walking performance assessed by the SPPB was contrasted with IMU-derived gait metrics, revealing clear differences between performance groups (IV). Participants classified in the $>$ 8.70 s category exhibited lower gait speed compared to those in the 6.21–8.70 s group. In contrast, cadence values were higher in the $>$ 8.70 s group (72.05 ± 6.75 steps/min) than in the 6.21–8.70 s group (69.24 ± 6.62 steps/min).

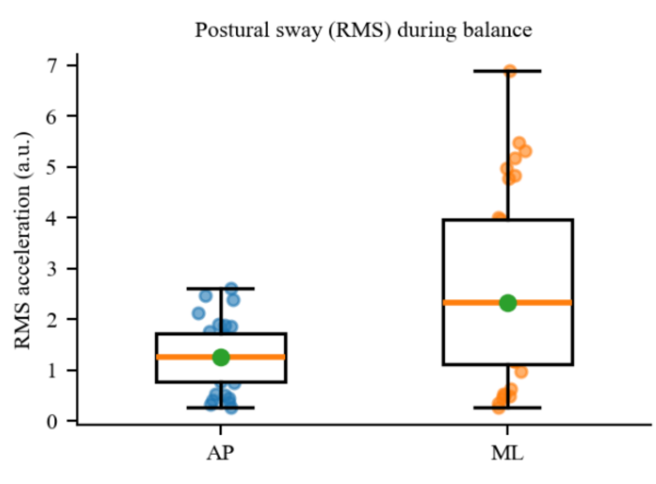

Fig. 7. Postural sway (RMS) during balance

Directional differences in postural sway were observed during the balance task, with higher RMS acceleration values in the mediolateral (ML) direction compared to the anteroposterior (AP) axis (7). The ML component also showed greater inter-individual variability, as indicated by a wider interquartile range and increased dispersion of individual measurements.

While the SPPB balance subtest provides a categorical assessment of postural stability, the IMU-derived RMS metrics allow for a continuous and direction-specific quantification of sway, revealing differences between AP and ML control strategies.

Despite comparable overall chair stand performance, marked differences emerged at the repetition level. One participant demonstrated rapid adaptation followed by stable execution times, whereas another showed a clear increase in sit-to-stand duration during the final repetition, suggestive of performance deterioration (Fig. 8). These patterns highlight inter-individual variability in task execution that is not captured by total chair stand time alone.

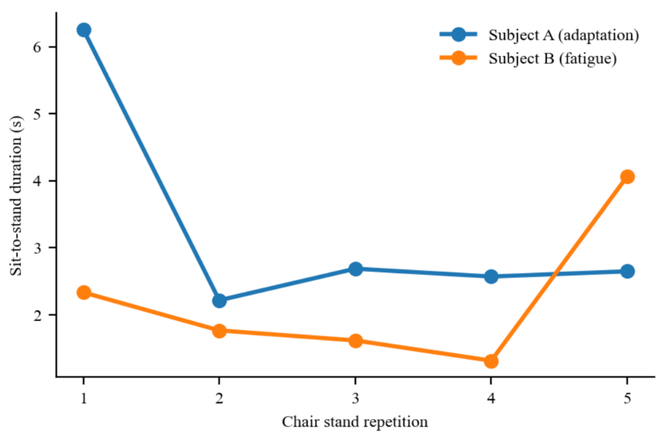

Fig. 8. Changes in sit-to-stand duration across successive chair stand repetitions for two representative subjects, showing adaptation and fatigue trends.

IV. Discussion

The IMU-derived metrics summarized in Table III provide an objective and continuous characterization of the functional domains evaluated by the SPPB, including gait performance, balance control, and lower-limb strength. Overall, the observed median gait speed of 0.437 m/s falls well below the 0.8 m/s threshold commonly associated with adverse outcomes in older adults, consistent with impaired physical performance and the lower SPPB walking scores recorded in this cohort. The median cadence of 63.2 steps/min remains substantially below typical reference values for healthy community-dwelling older adults (90–120 steps/min), reflecting a globally slow locomotor pattern. When stratified by SPPB walk category (Table IV), participants in the >8.70 s group exhibited slightly higher cadence (72.05 ± 6.75 steps/min) than the 6.21–8.70 s group (69.24 ± 6.62 steps/min) despite lower gait speed, suggesting a partial compensatory strategy through increased step frequency in response to reduced step length.

Balance-related metrics demonstrated greater variability in the mediolateral (ML) direction (RMS: 2.331 m/s²) compared to the anteroposterior (AP) axis (RMS: 1.253 m/s²), with ML RMS nearly twice the AP value (Fig. 7). This finding is clinically relevant, as ML instability has been widely reported as a sensitive marker of balance impairment and fall risk in older adults. In contrast, the more constrained AP sway observed in this study may reflect preserved sagittal-plane control, while deficits in frontal-plane stability indicate early functional deterioration. These observations are consistent with the balance component of the SPPB, which penalizes impaired postural control during static standing tasks but does not quantify directional instability.

Regarding lower-limb function, the chair stand task revealed a median total execution time of 16.86 s and a negative duration slope (-0.116 s/rep), indicative of reduced muscular strength and progressive performance reduction across repetitions. While the SPPB captures chair stand performance using an ordinal score, the IMU-derived metrics enabled a more detailed analysis of movement execution, revealing repetition-level patterns suggestive of both adaptation and fatigue. Notably, participants with similar total chair stand times exhibited distinct temporal profiles across repetitions (Fig. 8), highlighting differences in functional reserve that are not discernible through aggregated clinical scores alone.

The heterogeneity observed in the clinical characteristics of the participants further underscores the limitations of relying exclusively on ordinal assessment tools. Factors such as comorbidities, medication use, and prior fall history may influence movement quality and variability without necessarily altering the overall SPPB score. In this context, the integration of IMU-derived metrics allowed for a more granular characterization of functional performance, capturing subtle alterations in gait and balance that may otherwise remain undetected.

Taken together, these findings support the complementary role of inertial sensors in functional assessment of older adults. By providing continuous, objective measures of movement quality and temporal variability, IMU-based analysis enhances the sensitivity of traditional clinical tests such as the SPPB. This added resolution may be particularly valuable for identifying early signs of performance deterioration, fatigue, or reduced functional reserve, thereby informing timely interventions aimed at preserving mobility and independence in aging populations.

V. Limitations and Recommendations

The sensing hardware could be refined to improve usability in older adults. Although the acquisition setup performed reliably, external rechargeable batteries were needed to ensure continuous power during testing. This solution allowed uninterrupted data collection, but it may have reduced comfort and affected the ergonomics of the wearable system.

The sample size was modest and restricted to a specific participant group, which limits generalizability and precludes more detailed subgroup analyses, including comparisons across frailty levels, age ranges, or sex.

The analytical approach was intentionally focused on core spatiotemporal gait parameters derived from the SPPB walking test. This favored clarity and interpretability, but it may have left more complex features within the inertial signals unexplored.

VI. Future Work

The proposed device will next be evaluated as an objective monitoring tool within the VIVIFRAIL program, where exercise prescriptions are tailored according to functional stratification based on SPPB scores. Linking inertial-based measurements with the program's exercise levels could help quantify functional changes associated with structured physical interventions.

Longitudinal implementation of this approach could allow continuous monitoring of mobility-related parameters over time, making it possible to evaluate changes in functional performance and frailty status throughout the intervention process. Repeated assessments performed during follow-up periods may provide additional insight into movement evolution, recovery trends, and transitions between frailty states in older adults.

More broadly, this approach may contribute to the incorporation of accessible technology-based tools into routine functional assessment and follow-up of older adults.

VII. Conclusion

The integration of low-cost inertial measurement units into the SPPB was feasible for functional assessment in older adults. IMU-derived metrics were obtained during standard test execution without affecting performance, allowing gait, balance, and chair stand outcomes to be described through objective and continuous measures alongside conventional clinical scoring.

Instrumented analysis provided information beyond ordinal SPPB categories. The cohort exhibited a median gait speed of 0.437 m/s and a cadence of 63.2 steps/min, values consistent with reduced step length and slow locomotor pace typical of frailty. Postural sway showed a marked mediolateral predominance, highlighting directional differences in stability not captured by the categorical SPPB balance score. The chair stand task revealed a negative duration slope (-0.116 s/rep) and inter-individual differences in repetition-level dynamics despite comparable total execution times.

From a broader perspective, the instrumented SPPB offers a practical starting point for objective frailty assessment in Honduras, where this type of evaluation remains underexplored in both clinical practice and research. Its low cost and portability make it a promising tool for gradual integration into routine functional assessment.

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