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Designing, Development and Testing Reliability of Indigenously Developed Wearable IMU System to Measure Joint Kinematics, Center of Pressure and Spatiotemporal Gait Parameters in Normal Human Adults

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ABSTRACT

Background: Quantitative gait analysis is a critical tool for the objective measurement and assessment of human movement, yet it remains underutilized in clinical practice. This method is essential for diagnosing, managing, and treating locomotor impairments. Traditional laboratory equipment, such as optical motion-capture systems and force plates, is often regarded as the gold standard due to its high precision. However, their high costs and lack of portability limit their use in routine clinical settings. This study addresses these limitations by introducing a cost-effective, portable wearable gait analysis system that uses an Inertial Measurement Unit (IMU). The system is designed for versatility, enabling use in both outdoor and indoor environments.
Objective: The purpose of this experimental study was to comprehensively evaluate the reliability of the newly indigenously developed wearable IMU system for measuring joint kinematics in the sagittal plane and key spatiotemporal gait parameters in normal human adults.
Methods: This study involved a sample of 30 Normal adults (both genders), aged 20 to 45 years, with a body mass index of 18.5 to 24.9 kg/m^2. We developed a custom-designed wearable solution comprising an ISM330DHCX IMU, Force Sensitive Resistors (FSRs), a microcontroller, and an Arduino Nano-Raspberry Pi 4. All participants performed a 10-meter walk test, during which the system recorded joint kinematics in the sagittal plane and spatiotemporal gait parameters.
Results: The newly developed wearable gait analysis device demonstrated high reliability across most tested parameters, supporting its intended application. The SEM values for the ankle and hip joints in the sagittal plane were below 5 degrees, which is consistent with a clinically acceptable range. On the other hand, the knee joint kinematics exhibited a slightly higher SEM during the mid swing phase (6.7 degrees for the left limb and 6.9 degrees for the right limb). SEM values for all the spatiotemporal parameters, including step length, stance time, swing time, and cadence, ranged from 0.06 to 0.32, demonstrating strong agreement. The mean values of all measured parameters were in

accordance with established normative data for a normal human adult population.
Conclusion: The results show that the new compact wearable IMU system is a valid and reliable method for quantifying joint kinematics and spatiotemporal gait parameters. With its low measurement error, portability, and affordability, this system is well positioned as an alternative to conventional laboratory equipment. In this context, the potential of quantitative gait analysis is further realized, and its clinical and community applications open new avenues, with the diagnosis, monitoring, and treatment of locomotor deficits potentially assuming a larger role.

Keywords: Gait analysis, Wearable sensors, Inertial Measurement Units, Joint Kinematics, Spatiotemporal Gait Parameters, Rehabilitation

INTRODUCTION

Human locomotion is a complex motor task, and objective gait analysis provides valuable insights for managing conditions such as musculoskeletal diseases, neurological impairments, and post-injury rehabilitation [1]. Traditional motion analysis techniques, such as camera-based optical motion capture (OMC) and force plates, are recognised as the gold standard for their high accuracy and precision [2]. The widespread use of these methods in clinical settings is severely limited by high acquisition and maintenance costs, the need for a dedicated laboratory, and the lack of portability [3]. These limitations preclude their utility for continuous home-based monitoring, which is essential for a comprehensive understanding of a patient's functional status in real-world environments [4].

The advent of Micro-Electro-Mechanical Systems (MEMS) has spurred the development of wearable sensors, such as Inertial Measurement Units (IMUs), which include tri-axial accelerometers and gyroscopes and are affordable, offering a prospective alternative to traditional systems [5]. IMUs enable the collection of real-time kinematic and spatiotemporal data in natural, unconstrained environments. This has paved the way for a paradigm shift, allowing the objective assessment of gait not only in a clinical setting but also during a patient's daily activities [6]. Despite technological advances, there remains a critical need for validated, reliable, and indigenously developed solutions tailored to specific clinical applications [7].

The present study was designed to develop a novel wearable IMU system and to rigorously assess its test-retest reliability in measuring sagittal-plane lower-limb kinematics and spatiotemporal gait parameters in a normal adult human population. The study also compares results with normative reference values to support healthcare applications. These shifts enable gait evaluations not only in clinical settings but also during patients' daily activities. We hypothesized that the developed system would produce consistent, repeatable measurements comparable to established normative data.

MATERIALS & METHODS

The study used an experimental design to assess the test-retest reliability of a novel wearable IMU system. A convenience sample of 30 normal adults was recruited from the local population. The inclusion criteria consist of age from 20 years to 45 years, Body Mass Index (BMI) within the normal range (18.5-24.9 kg/m^2), and a tandem gait grade of 4 (normal) on a 10-step assessment [8]. Exclusion criteria included individuals with any known locomotor disability or those unable to comprehend and follow study instructions. Informed consent was secured from all participants, and the research adhered to the ethical guidelines set forth by the Institutional Ethics Committee.

Every component selection, such as the part that fulfills its part-of-need for its use case, enables an integrated development approach. As the assembly step integrates the selected components into a complete solution, and integrates them in accordance with defined parts of the specification, with each component in its own way, and there is a function available for its use, the overall functionality is optional. The Inertial Measurement Unit (IMU) calibration with appropriate data flow is a fundamental requirement for precision and accuracy in motion analysis and is vital to this procedure. That is a critical calibration; it is crucial in generating reliable outputs. The system is fitted after completion, and the key features run from the analysed data. Initial development of the prototype is a hands-on exercise for evaluating the performance of the system. A robust testing process is run for this prototype to validate the performance constraints and pinpoint any possible weaknesses. Test feedback contributes to the final hardware assembly and a refined version of the system, integrating enhancements based upon empirical data and user experience. The addition of additional accessories also improves the usability and applicability of the system.

The above provides a general overview of the components that contributed to this system's creation, as well as its complexity and performance levels. Thus, the ISM330DHCX IMU provides three-dimensional motion accurately, in hardware, as in a high-dimensional view, with the Raspberry Pi 4 microprocessor supporting the computational system required to complete complex applications and data manipulation tasks. The Qwiic HAT enables integration of various components, promotes modularity, and reduces assembly complexity. Our plan for circuit assembly is tightly oriented to facilitate smooth data transmission between the different IMUs and FSRs. All IMUs are interspersed 12C multiplexed, enabling efficient communication and are free from the interference of multiple devices. The operational protocol of the IMU is composed of critical operational stages: initial validation for hardware function, running of the data based on user engagement, error detection to inform the user of operating errors, and integrity maintenance of the data generated during the data collection process, which can be prepared for further analysis. But utilizing such as integrated design approach, the resultant wearable inertial measurement system can be properly configured to support gait analysis, providing an essential insight into foot pressure dynamics and progress to improving overall walking functionality. The method-guided design of the device not only improves the functionality of biomechanical wearables but also lays the foundation for innovation in other motion analysis systems.

IMU System Architecture

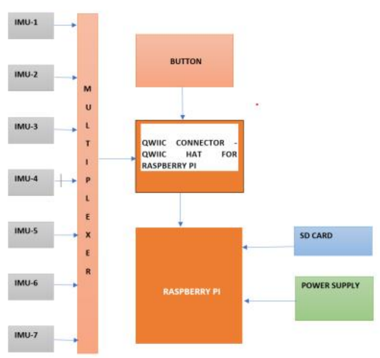


Figure1. Block Diagram of IMU Sensors Module

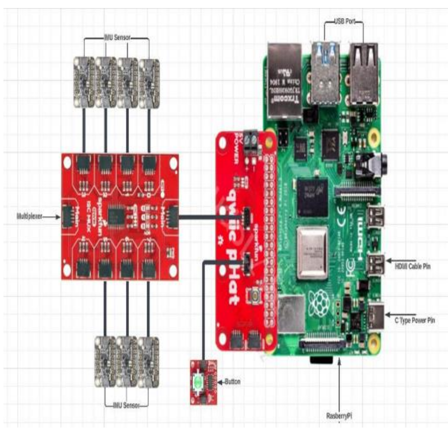


Figure 2. Circuit Diagram

As depicted in Figure 1, the created IMU system consists of seven separate IMUs, with each unit containing an accelerometer, a magnetometer, and a gyroscope. The data from all sensors is multiplexed and stored in a central microcontroller at a sampling rate of 100 Hz on an 30 SD card, forming the IMU system.

Device Design and Components

The developed wearable system consists of two main components: a wearable joint angle sensor and a shoe-based sensor system, both controlled by a central processing unit.

Inertial Measurement Unit (IMU)

An ISM330DHCX sensor measures linear acceleration and angular velocity across 3 axes, providing 6 degrees of freedom for precise joint-angle determination with the help of sensor-fusion algorithm [9]. Its efficient power use allows long-term deployment in embedded systems. By virtue of temperature range of -40 to 105 degrees, it maintains data accuracy in various conditions, ensuring reliability for critical applications. Each sensor is equipped with an accelerometer and a gyroscope on a single silicon substrate, ensuring exceptional synchronisation of measurements.

Microprocessor- Raspberry Pi 4 Model B

Built for performance equal to entry-level PCs, the Raspberry Pi 4 Model B is the key driver for this wearable system. Featuring dual 4K displays and an array of connectivity options, this microprocessor is adept at efficiently processing complex applications and data sets.

Qwiic Connector Overview-Qwiic HAT for Raspberry Pi

Qwiic HAT enables integration between the Raspberry Pi and other Qwiic-compatible devices and simplifies assembly and increases modularity. It is designed to create daisy-chaining of several sensors on one 12C bus, which is more efficient in setup and removes spatial constraints. This makes assembly easier and setup efforts more efficient without the burden of spatial constraints.

Circuit Assembly and Data Management

A clearly outlined circuit diagram effectively identifies the link between many IMUs and FSR sensors, so that their specific data can be transmitted and utilised efficiently in its entirety of the circuit. Each IMU is to pass through a 12C multiplexer in order to allow seamless data exchange without interference. Including a Qwiic button makes it easier for the user to engage with data and allows users to collect feedback by clicking a button.

Pressure Sensors

The shoe insole was equipped with FSR to measure the change in pressure [10]. Binary values (on/off) provide pressure-sensing input for the gait cycle phases (heel strike, toe-off). Sensors were interacted with an Arduino Nano, and the raw data was collected and later relayed to a Raspberry Pi Model B.

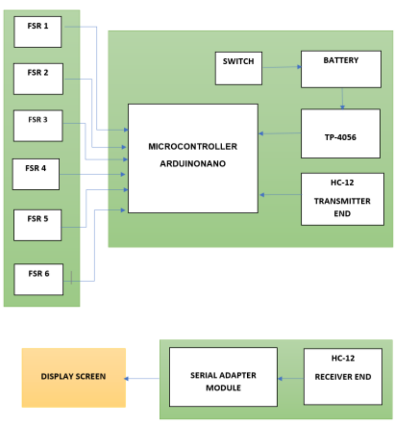


Figure 3. Block Diagram of Pressure Mapping Module

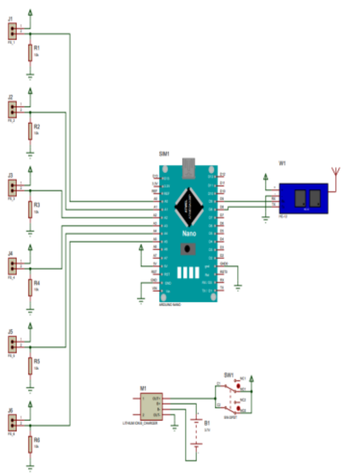


Figure 4. Circuit Diagram of Pressure Sensors

The Raspberry Pi served as the central processor, running the data analysis algorithm and providing visual feedback.

Wireless Communication

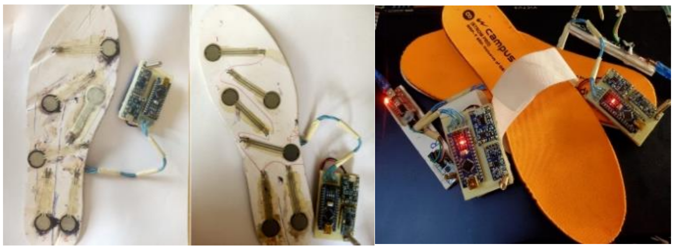


Figure 5. Pressure Measuring Insoles

An HC-12 module ensured reliable, long-distance wireless transmission of data for communication between sensors and processing unit, securing data integrity during the walking test [11].

Figure 6. Assembled view of Inertial Measurement Unit (IMU) System

Data Collection Protocol

The study protocol included three separate data sessions per participant to assess test-retest reliability. The sessions spaced out to reduce the effects of short-term fatigue. During each session, sensors were securely attached to the participant's lower limbs at anatomically defined locations. Participants were then asked to perform a 10-meter walk test at a self-selected comfortable speed. The system recorded data for multiple gait cycles, and a single cycle was chosen for analysis. The protocol aimed to minimize potential errors caused by sensor misplacement and drift, known challenges for the IMU system.

Statistical Analysis

Data analysis was executed by the statistical tool using the GraphPad Prism 4.8.2 software, a standard statistical software. Reliability was assessed using the SEM (Standard Error of Measurement), a measure of the degree of random error in a measurement. A smaller SEM represents a more reliable and consistent measurement. The data were compared against established normative values to check the accuracy of the system, as reported in the literature.

RESULT

The mean values for spatiotemporal and kinematic parameters were found to be within typical ranges reported in the literature for healthy adults.

The IMU system demonstrated strong agreement with the normative values for both left and right lower limbs. The SEM values for the kinematics of the hip, knee, and ankle joints were low, which implied high reliability. The spatiotemporal parameters were highly consistent throughout, validating the reproducibility of the system.

Table 1. Mean ± standard deviation (SD) for session 1 and session 2 along with Standard

		SESSION 1	SESSION 2	
GAIT PARAMETERS	SIDE	MEAN±SD	MEAN ±SD	SEM
STANCE %	L	61.66±1.36	61.94±1.48	0.11
	R	61.29±1.20	61.62±1.32	0.11
SWING %	L	38.34±1.36	38.06±1.48	0.06
	R	38.71±1.20	38.34±1.36	0.06
STEP LENGTH	L	0.70±0.04	0.68±0.03	0.12
	R	0.69±0.04	0.68±0.03	0.12
STRIDE LENGTH	L	1.39±0.07	1.37±0.05	0.24
	R	1.37±0.12	1.38±0.06	0.25
CADENCE		109.1±4.3	109.4±5.1	0.32
GAIT SPEED		1.43±0.05	1.44±0.05	0.26

Error of Measurement (SEM) for spatiotemporal gait parameters.

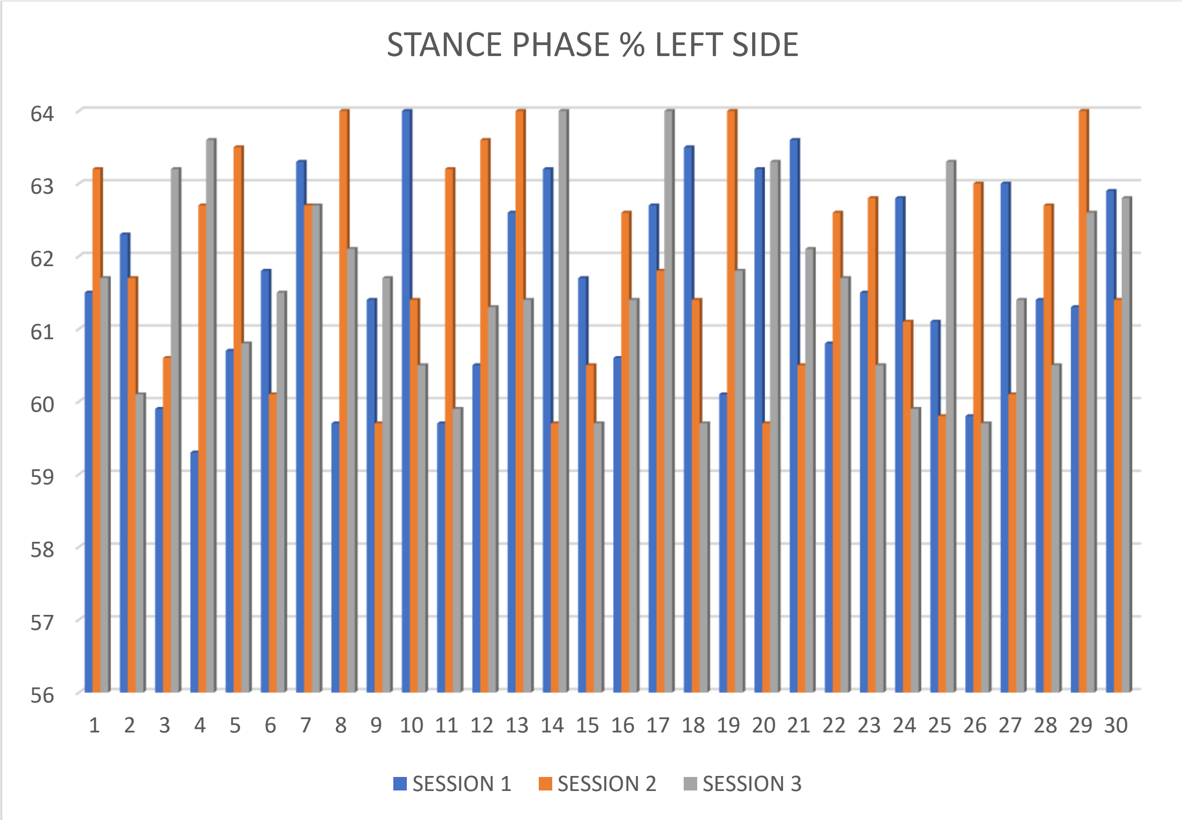
Kinematic gait analysis showed that the standard error of measurement SEM values were less than 5 degrees for all the joints in the sagittal plane except for the knee joint in the mid-swing phase, which recorded SEM values of 6.7 degrees for the left knee and 6.9 degrees for the right. While this difference is above recommended upper limits, it represents a high accuracy in biomechanical research. Measurement errors were usually between 2 to 5 degrees, which is acceptable. Using the gait parameters demonstrated stability in two sessions, where the stance percentage averaged around 61% for both limbs and swing percentage was around 38%. The average step lengths were anywhere from 0.69 m to 0.70 m. Furthermore, stride lengths and cadence were stable, which showed stable rhythmic gait.

Table 2. Mean ± standard deviation (SD) for session 1 and session 2, along with Standard

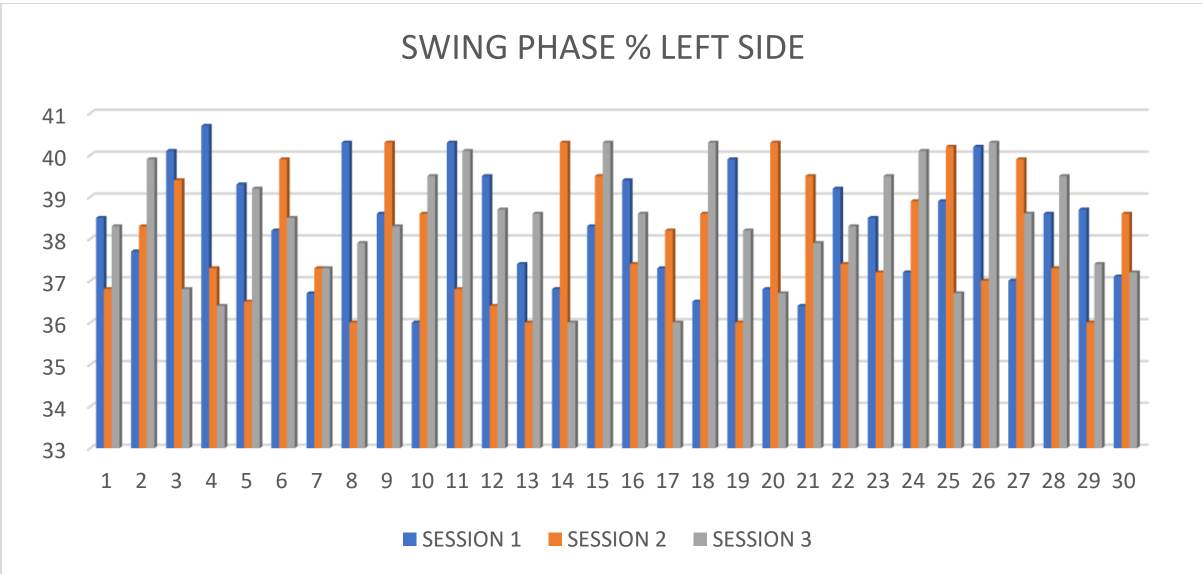
			SESSION 1	SESSION 2	
JOINT	**GAIT PHASE**	**SIDE**	**MEAN±SD**	**MEAN±SD**	**SEM**
HIP	Initial stance	L	24.22±3.4	26.63±3.3	4.6
		R	24.87±3.9	27.27±2.7	4.7
	Mid stance	L	14.65±3.0	16.21±3.5	2.8
		R	14.66±3.4	14.71±3.2	2.6
	Terminal stance	L	12.04±3.7	12.67±3.9	2.2
		R	12.11±3.5	12.61±3.4	2.2
	Mid swing	L	19.57±5.8	18.91±7.7	3.5
		R	16.87±6.8	19.17±7.5	3.3
KNEE	Initial stance	L	1.91±1.4	2.08±1.5	0.3
		R	2.0±1.5	2.17±1.6	0.4
	Mid stance	L	12.27±2.8	12.05±3.07	2.2
		R	11.87±3.3	12.33±3.2	2.2
	Terminal stance	L	20.8±4.6	20.05±5.4	3.7
		R	21.51±4.9	21.71±4.9	3.9
	Mid swing	L	36.41±7.7	37.74±6.9	6.7
		R	37.82±6.6	38.35±5.6	6.9
ANKLE	Initial stance	L	3.14±1.5	3.28±1.2	0.5
		R	2.94±1.4	3.30±1.9	1.7
	Mid stance	L	3.16±1.4	2.92±1.6	0.5
		R	3.35±1.1	2.67±1.6	0.5
	Terminal stance	L	18.58±2.4	18.07±2.3	3.3
		R	17.55±2.1	18.11±2.1	3.2
	Mid swing	L	3.34±1.5	3.09±1.4	0.5
		R	2.6±1.2	2.84±1.2	0.4

Error of Measurement (SEM) for sagittal plane joint kinematics.

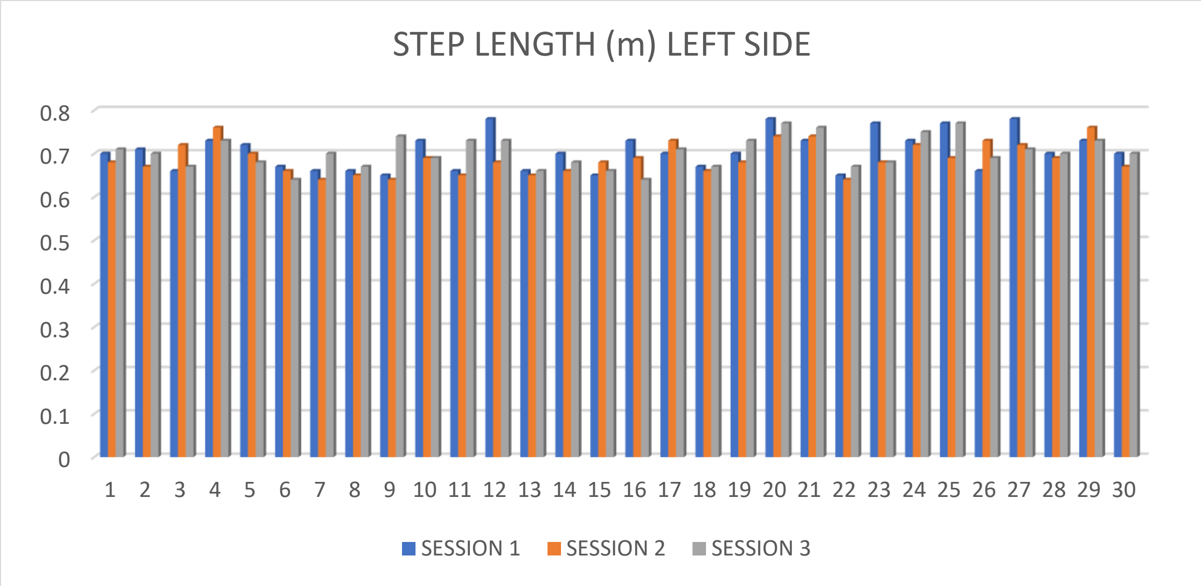
Measurements taken from the hip, knee, and ankle in initial, mid, and terminal stances were within established reference ranges, with no significant differences between IMU-recorded values and these references. These results demonstrate that IMU data can be reliable for assessing spatiotemporal gait parameters and joint angles within this population.



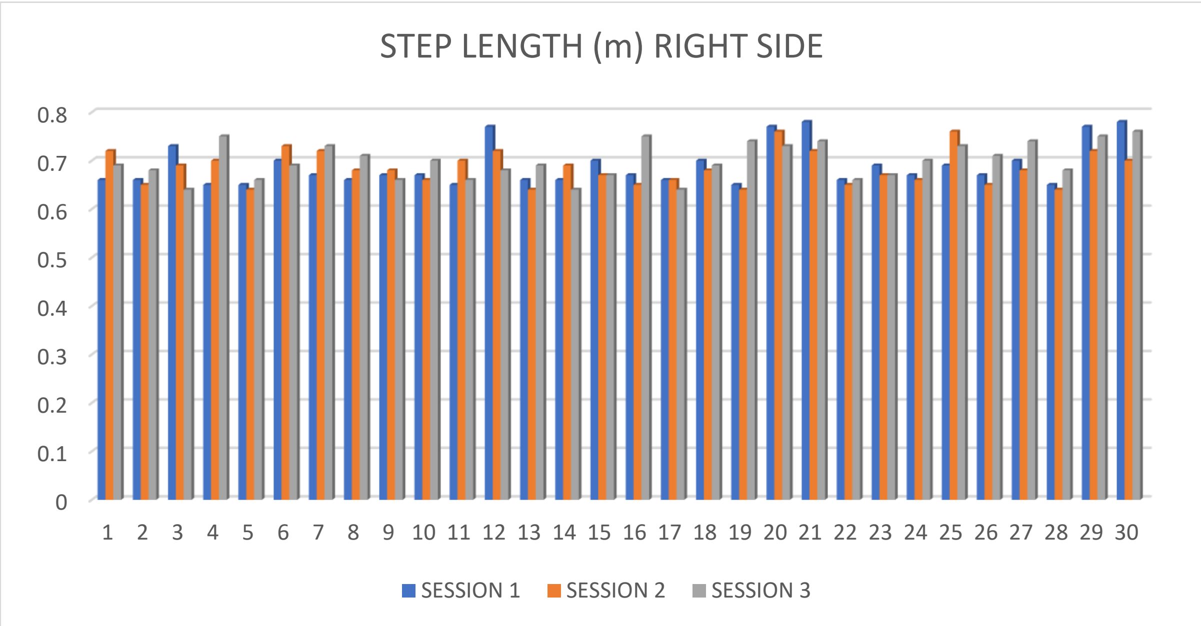
X axis – Number of subjects
Y axis – Stance phase percentage (%)
Graph 1: Stance Phase Percentage of the left side of 30 participants obtained in three sessions.



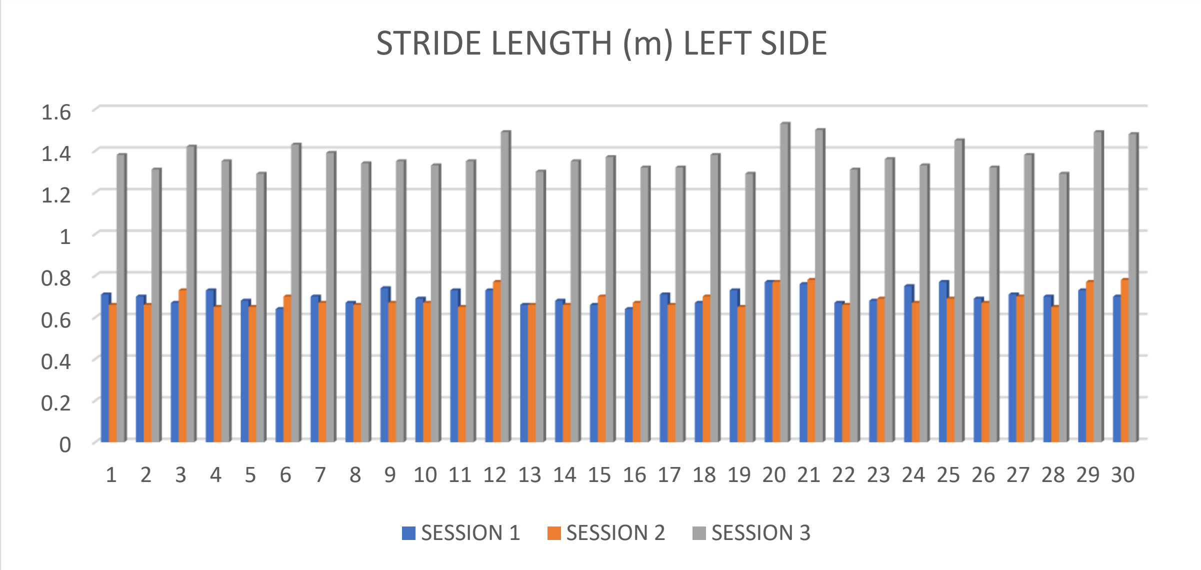
X axis – Number of subjects
Y axis – Swing phase percentage (%)
Graph 2: Swing Phase Percentage of the left side of 30 participants obtained in three sessions.



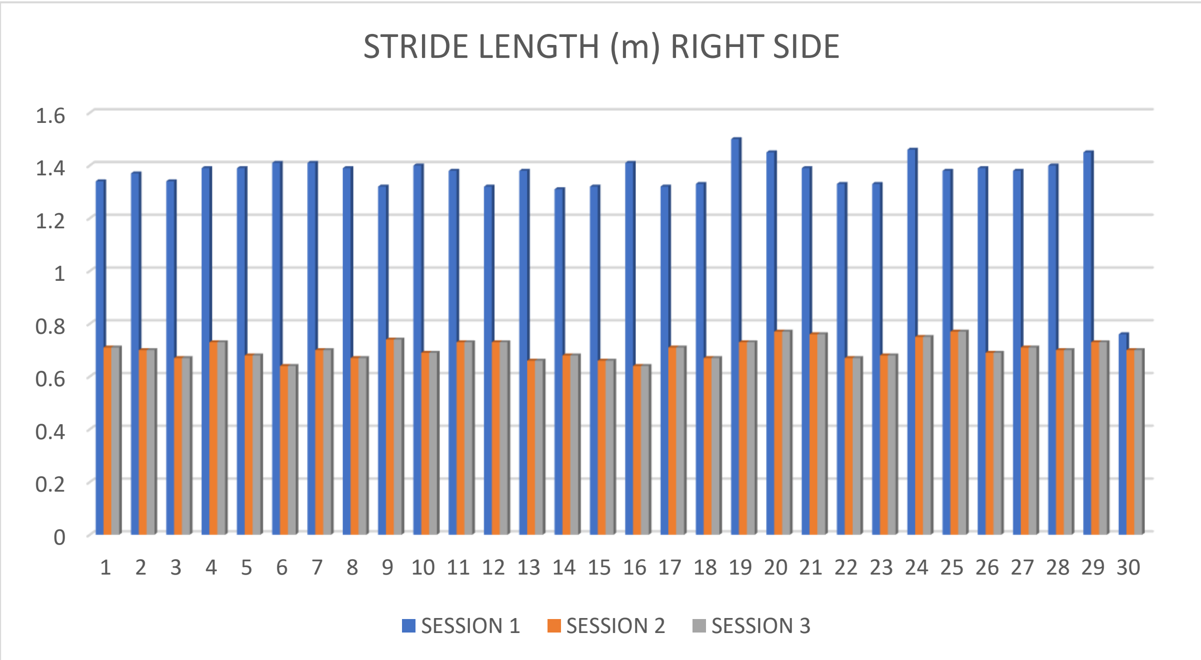
X axis – Number of subjects
Y axis – Step Length
Graph 3: Step length of the left side of 30 participants obtained in three sessions.



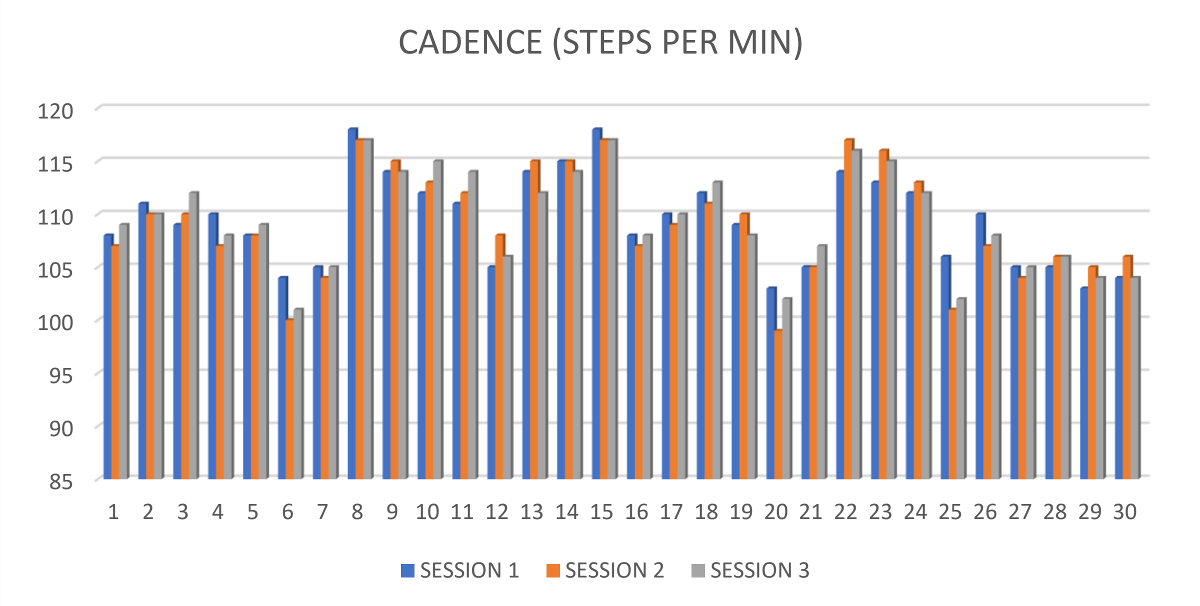
X axis – Number of subjects
Y axis – Step Length
Graph 4: Step length of the right side of 30 participants obtained in three sessions.



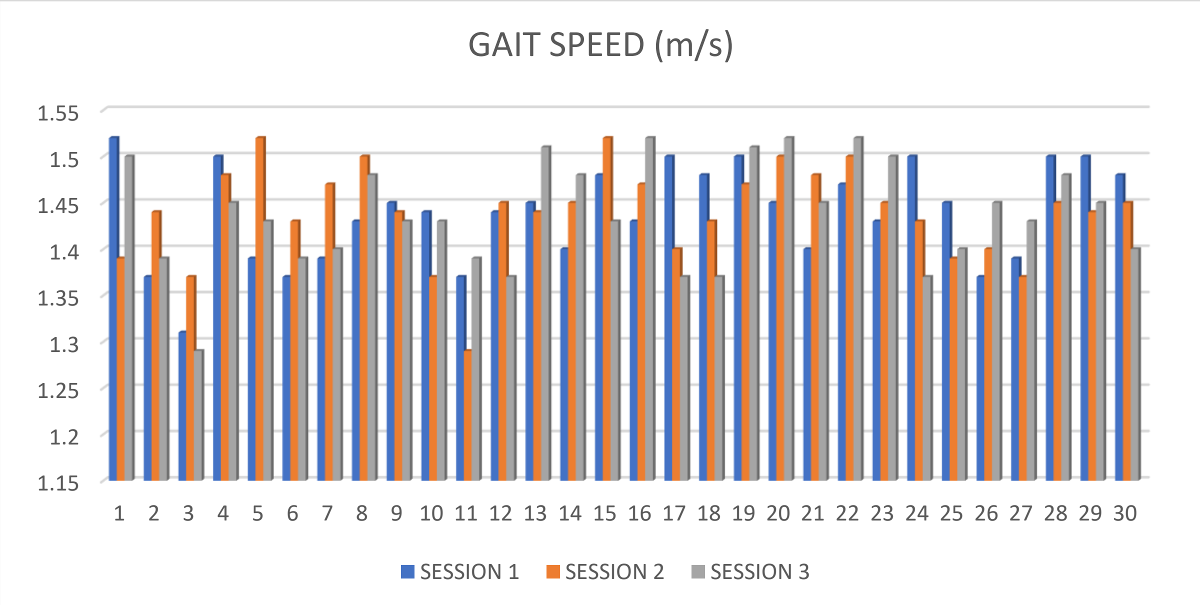
X axis – Number of subjects
Y axis – Stride Length
Graph 5: Stride length of the left side of 30 participants obtained in three sessions.



X axis – Number of subjects
Y axis – Stride Length
Graph 6: Stride length of the right side of 30 participants obtained in three sessions.



X axis – Number of subjects
Y axis – Cadence
Graph 7: Cadence of 30 participants obtained in three sessions.



X axis – Number of subjects
Y axis – Gait Speed
Graph 8: Gait Speed of 30 participants obtained in three sessions.

The only exception appeared at the knee joint during mid-swing, where SEMs were slightly elevated 6.7 degrees for the left and 6.9 degrees for the right knee. Joint angle analysis across key stages, initial, mid and terminal stances, indicated findings were in good agreement with references points of hip, knee and ankle.

Of significance was that there was no significant difference between IMU and reference standards. This strengthens the trustworthiness of IMU technology for the evaluation of spatiotemporal gait parameters, and the tracking of joint movements.

In general, this report provides strong evidence that IMU data is capable of quantifying the spatiotemporal gait parameters and joint angles in our population. Such confidence provides opportunities in clinical practice to be employed as part of rehabilitation that can enhance mobility and improve musculoskeletal health as a whole.

DISCUSSION

The results from the study confirm that the indigenously developed wearable IMU system is a consistent and reliable gait analysis tool. The low SEM measurements for both kinematics and spatiotemporal parameters are remarkable, demonstrating its ability to provide repeatable measurements such as those necessary for clinical applications where tracking patient progress is paramount. These findings are in line with the broader scientific literature, which has established the "excellent" validity and reliability of IMUs assessing these parameters [12].

The observed slight increases in SEM for knee kinematics during the mid-swing phase is a common issue reported on IMU based systems. This can be attributed to the multi-planar motion with rapid acceleration changes of the knee joint during the non-weight-bearing phase [13]. Unlike the stance, ground contact provides a clear reference point, the swing phase relies heavily on the IMU's internal measurement, making it more susceptible to errors such as integration drift [14]. Despite this, the SEM values observed in our study remain within a range that is often considered clinically acceptable for tracking progress or making treatment decisions [15].

The system's portability, affordability, and real-time data capabilities address a critical need for accessible gait analysis, moving it from a specialized laboratory procedure to a routine clinical assessment. The development of such devices enables the concept of a "mobile gait lab", allowing for long-term, continuous monitoring in a patient's natural environment. This is highly beneficial for assessing the effectiveness of interventions and providing telerehabilitation services [16].

Participants also underwent a tandem gait assessment, where a score of 4 was required for inclusion. Yoo et al. [8] highlighted the significance of the 10-step tandem gait test as a crucial screening tool for individuals experiencing minor gait or balance disturbances, who may not perceive any walking abnormalities. The age range for participant selection spanned from 20 to 45 years. Gait parameters vary significantly across age [17]. The physical changes occurring in joints as individuals age can affect their gait patterns, which is why the chosen age limit for this study was set to mitigate such variances.

The efficacy of the system was evaluated by analysing two consecutive sessions result for error assessment, employing methods akin to those described by Riazati Sherveen and McGurik Theresa E [18] regarding Absolute Reliability in gait parameters. According to Weir, J.P. (2005) [19], absolute reliability metrics offer valuable insights into the measurement error inherent to the equipment and expected variability in data across trials.

The findings from this study indicate that the wearable IMU system exhibits an acceptable level of measurement error. Notably, measurement errors for sagittal plane joint angles collected from the system remained under 5 degrees for both hip and ankle joints on both sides. The knee joint also demonstrated a measurement error of less than 5 degrees across all gait phases, except for midswing on both sides. These narrow error margins validate the system's reliability, as discussed by Albani et al. (2014) [20], who identified noteworthy sagittal plane kinematic disparities between normal individuals and those diagnosed with Parkinson's disease.

In terms of spatiotemporal parameters, widely recognized as vital indicators of clinical outcomes, the recorded Standard Error of Measurement (SEM) spanned from 0.06 to 0.32, underscoring the reliability of the wearable IMU system in evaluating clinical outcomes.

These findings are consistent with the literature, indicating "excellent" validity and reliability of IMUs for these specific factors. A small increase in SEM for knee kinematics at the midswing phase is consistent with common linitations found in IMU-based systems. This may be attributed to the complex multi-planar motions and abrupt changes in acceleration of the knee joint in non-weight-bearing activities [21]. In contrast to stance phases, which offer an explicit reference point from grounded interaction, there is a heavy reliance on IMU internal measurements, making them susceptible to errors, including integration drift [22]. However, the SEM values measured in our study remain clinically relevant for assessing patient progress or treatment, informing decision-making.

The results showed that this wearable IMU system displayed acceptable measurement error rates, between session errors indicate that sagittal plane joint angles, remained below five degrees bilaterally, which represent low margin errors, reinforcing reliability, as seen from Albani et al. (2014)

Limitations

The study's limitations include its relatively small size and the use of convenience sampling. In addition, it was performed on a healthy, young adult population, and the system's performance may differ in individuals with pathological gaits, who often exhibit more complex and variable movement patterns.

Future Directions

Formal validations of its accuracy against a gold standard optical motion capture system are warranted in future work. Additionally, testing the device on populations with various locomotor disorders is necessary to determine its clinical utility in diagnosing and tracking disease progression in real-world settings.

CONCLUSION

The study successfully designed, developed, and proved a reliable wearable IMU system for gait analysis. The low degree of measurement error found in the sagittal plane kinematics and spatiotemporal parameters indicates that the device is sensitive enough to detect small changes in clinically significant outcomes. The proposed system presents a portable, cost-effective, and intuitive approach with immense potential to increase the accessibility of quantitative gait analysis and its application in clinical settings and research studies.

An innovative Wearable Inertial Measurement Unit (IMU) system is designed and developed in this work to measure sagittal plane joint kinematics and spatiotemporal gait parameters. After development, the device's reliability was to be established. The developed wearable IMU system was tested on 30 subjects for 3 sessions using the 10 m walk test. The developed wearable IMU system would provide confidence in detecting gait pathology and in monitoring outcomes in response to rehabilitation. This data can be transferred to the indices required for disease analysis and used in both indoor and outdoor environments. Finally, information from the wearable system is less susceptible to user privacy concerns.

Thus, the intelligent wearable IMU system stands out as a promising advancement in the realm of gait analysis and rehabilitation monitoring, equipped with the precision needed to support clinical decision-making and improve patient outcomes.

Declaration by Authors
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Conflict of Interest: None

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