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COMPARATIVE STUDY OF THE FREQUENCY RESPONSE OF SMARTWATCH SENSORS FOR HUMAN MOVEMENT ASSESSMENT

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ABSTRACT

Smartwatches are wearable devices designed for continuous and precise data collection, ensuring minimal disruption or discomfort for the user. Their ability to monitor movement makes them particularly effective for applications such as health monitoring or workplace risk evaluation. However, the inertial sensors embedded in these devices may exhibit inaccuracies in data acquisition, which could compromise the quality of the results. Therefore, thorough characterization is essential to understand their response under specific excitation conditions.

This study evaluates the performance of accelerometers in four commercially available smartwatches, by assessing their frequency responses using two different calibration methods. Method 1, considered the reference method and involving individual sensor calibration, produced minimal deviations, validating the reliability of the devices within the tested ranges. In contrast, Method 2, intended for quicker calibration of multiple devices, showed greater deviations due to limitations in the calibration process.

The results revealed discrepancies in performance based on the calibration method used, highlighting the importance of selecting an appropriate technique to ensure more reliable and accurate measurements, especially for critical human movement monitoring applications.

Keywords: *calibration, accelerometer, wearables, human movement monitoring.*

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1. INTRODUCTION

Wearable technology has experienced significant growth in recent years, driven by the integration of advanced sensors into portable devices such as smartwatches, smart glasses, or biometric rings. These systems are widely adopted due to their ease of use, portability, and real-time data collection capabilities. Their main applications include occupational risk assessment, human movement and physical activity analysis [1], with increasing potential in healthcare [2]. Nevertheless, despite their advanced capabilities, multiple studies [3-5] have identified critical technical limitations in the embedded sensors of these devices, particularly regarding the accuracy and reliability of data acquisition.

Smartwatches are among the most common and widely adopted wearable devices [1] due to user familiarity and their integration into daily life. These devices are equipped with inertial sensors, including triaxial accelerometers and gyroscopes. The combined use of these sensors enables a detailed analysis of the user's dynamic behavior.

Periodic calibration or verification of sensors is essential, as factors such as environmental variations, temporal drift or device configuration changes can affect measurement reliability. To address this challenge, a thorough analysis of the sensor's dynamic behavior is required, focusing on its frequency and amplitude response under controlled vibratory excitation conditions [5]. This evaluation allows for the identification of the ranges where the sensor performs with maximum accuracy, while also revealing potential limitations in its measurement capabilities.

This study focuses on the characterization of accelerometers integrated into four commercial smartwatches of the same specific model. In healthcare and other movement monitoring studies, it is common to work with multiple identical devices. Therefore, ensuring that all devices

exhibit a similar and consistent response is essential for making reliable comparisons between the recorded data.
It is essential to determine the relevant amplitude and frequency ranges associated with human movement dynamics (hand-arm), with the aim of aligning the procedure with the specific operating conditions of the sensor. In this context, the frequency ranges extend up to 10 Hz, corresponding to physiological tremors [6], while typical amplitudes reach 4 m/s², as observed during human gait [7]. These parameters enable the assessment of smartwatch accelerometers in real-world applications.
This study employs two approaches for characterizing accelerometers to compare and analyze sensor performance variations under different calibration procedures.
The first method uses a uniaxial vibration bench, which allows for individual sensor characterization by applying precise vibratory excitation at different frequencies and amplitudes. While effective in terms of accuracy, this method can be time-consuming when calibrating multiple devices sequentially, making it less efficient for large-scale applications. This method was validated in [5], and is therefore considered the reference approach for comparison.
The second method utilizes a vibration platform, which generates vibrations on a surface. Unlike the previous approach, it allows for the simultaneous evaluation of multiple sensors, significantly reducing calibration time.
The study focuses on the comparative evaluation of the two calibration methodologies mentioned, employed to characterize accelerometers in smartwatches [8]. Through this analysis, the aim is to identify the advantages and limitations of each method in assessing sensor performance within the frequency and amplitude ranges associated with human movement. The ultimate goal is to optimize the calibration procedure, enhancing the reliability of measurements in biomechanical applications.

2. CALIBRATION METHODOLOGY

In studies related to human movement monitoring, particularly in healthcare or in safety fields such as risk assessments, multiple devices of the same type and model are typically used. Therefore, it is crucial that the data recorded by these sensors are comparable, meaning that all sensors must exhibit a precise and consistent response when subjected to the same mechanical vibration signal.
Consequently, this study focuses on characterizing the integrated accelerometers of four commercially available smartwatches of the same model by analyzing their frequency and amplitude response and verifying the consistency of their behavior. The sensors were configured with a sampling rate of 50 Hz and a maximum amplitude range of ±2 g, values considered appropriate for recording typical human movement dynamics in real-world scenarios.
Considering that the main objective of this study is not to fully characterize the accelerometer but to compare two calibration methodologies and evaluate their effectiveness, the analysis was intentionally limited to examining the frequency response of the Z-axis of the sensor. The axes orientation in the employed devices is shown in Figure 1.

Figure 1. Axes orientation in the employed sensor.

A vibratory excitation source is a device specifically designed to generate controlled vibrations, adjustable in terms of both frequency and amplitude, with the aim of subjecting sensors to defined testing conditions. The input signal applied is a sinusoidal waveform, as shown in Figure 2, whose characteristics are defined according to the sampling plan specifically designed for each study.

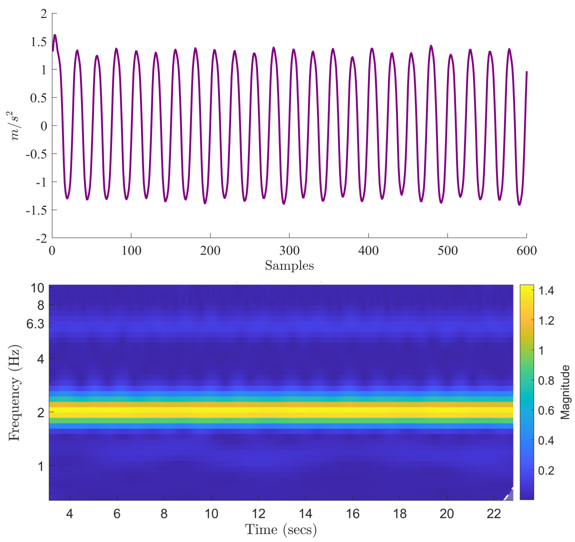

Figure 2. Signal captured by the accelerometer in a 2 Hz and 1 m/s² test. Top: time signal; Bottom: scalogram.

The quality of the calibration process is highly dependent on the performance of the excitation source. This study

employs two methodologies, each involving a different excitation source: Method 1, based on a uniaxial vibration bench, which enables the individual calibration of accelerometers through the application of precise and controlled vibrations; and Method 2, which utilizes a vibration platform capable of subjecting multiple sensors to uniform oscillations simultaneously, with the vibrations applied at a 45º angle relative to the horizontal plane.
The characterization of accelerometers is performed following the ISO 16063-21:2003 [9], which establishes a comparison methodology based on the use of a reference transducer. This method consists of rigidly coupling a calibrated reference accelerometer, which is presumed to function with a high level of accuracy, to the structure of the smartwatch, ensuring that both sensors are simultaneously exposed to the same controlled mechanical vibration.

2.1 Sampling plan

It is essential to establish a sampling protocol that clearly defines the specific frequencies and amplitudes to be used during the calibration process. It should guarantee that the characterization of the sensors is performed under controlled conditions that accurately replicate typical real-world hand-arm vibration scenarios.
Regarding the frequencies to be used for calibration, ISO 16063-21:2003 [9] recommends performing sensor characterization using vibratory excitations at standardized one-third octave frequencies, defined by ISO 266:1997 [10]. In the context of accelerometers designed for human movement analysis, it is crucial to adapt the excitation parameters to the typical frequency range characteristic of human activities in a variety of real-world contexts, which remains below 10 Hz [6, 11]. Accordingly, this study selected the frequencies of 1 Hz, 2 Hz, 4 Hz, 6.3 Hz, 8 Hz, and 10 Hz to evaluate the sensors' frequency response.
Concerning amplitude, the calibration was performed within an acceleration range of 1 m/s² to 4 m/s², reflecting the magnitudes encountered during common activities such as walking, running, or manual operations [7].
However, to develop a sampling plan suited to each calibration method, it is essential to carefully determine the operating range of the vibration sources used. In this context, multiple tests were conducted, establishing the operational interval for each method, as shown in Figure 3.
The common range shared by both calibration methods reaches up to 4 m/s² within the frequency band of 4 Hz to 6.3 Hz and decreases to 1 m/s² at 2 Hz. Method 1 offers the advantage of enabling excitations at higher frequencies (above 6.3 Hz), whereas Method 2 is particularly suitable for excitations at lower frequency ranges (below 4 Hz).

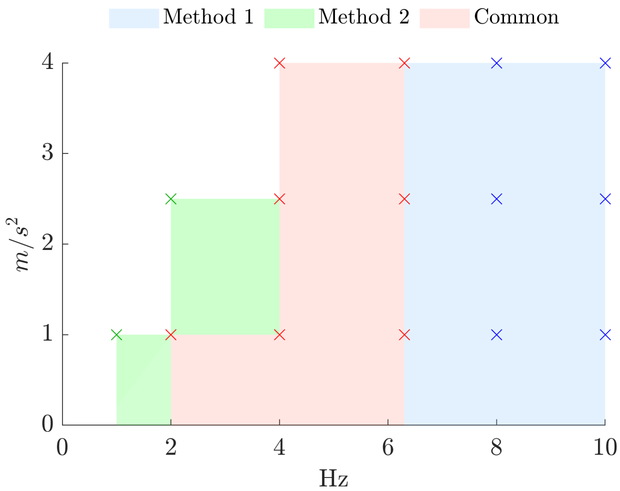

Figure 3. Specific operating range of the excitation sources in Method 1 and Method 2, including the common interval.

2.2 Setup

The calibration test setup is characterized by notable variations between both methods. In Method 1, the excitation source generates vibrations in a uniaxial configuration and, due to its geometric and dimensional constraints, it allows for the placement of only one device at a time, as shown in Figure 4 (left). Consequently, the smartwatch is positioned to ensure that the induced vibrations are applied exclusively along the Z-axis of its accelerometer. Additionally, the device is placed on a rigid and properly fixed holder, preventing the introduction of any undesired vibrations, guaranteeing the reliability and repeatability required for the calibration process.
In Method 2, the vibration excitation source consists of an actuator that induces vibrations on a platform at an angle of 45° relative to the horizontal plane, as illustrated in Figure 4 (right). Due to the dimensions of the surface where the vibration is generated, it is possible to place multiple devices simultaneously for calibration, thus facilitating a more efficient calibration process compared to Method 1.

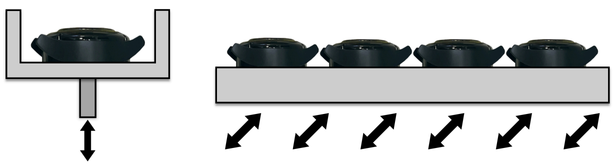

Figure 4. Movement induced by the excitation sources and placement of the smartwatches. Left: Method 1; right: Method 2.

Considering the characteristics of the excitation source in Method 2, there are two possible mounting configurations for placing the devices on the vibrating surface. The first option involves positioning the devices directly on the horizontal plane of the vibratory platform, as illustrated in Figure 5 (left). However, under this particular configuration, the excitation generated would simultaneously affect both the Z-axis and Y-axis of the device's accelerometer, resulting in a biaxial excitation. Although the mechanical implementation of this configuration is simple, it is not suitable for reproducing the Z-axis specific excitation carried out in Method 1.
Furthermore, to achieve the acceleration levels previously defined in the sampling plan, a, positioning the devices on the horizontal plane would necessitate that the platform generates an excitation with an amplitude equal to $\sqrt{2}a$, exceeding the acceleration levels intended for analysis during the calibration procedure. This requirement could lead to nonlinear behavior of the excitation source, particularly at low frequencies where higher amplitudes are required. Such nonlinearities may compromise the accuracy of the calibration and even pose a risk of structural damage to the platform due to excessive excitation levels.
In light of these considerations, the horizontal mounting option was deemed unsuitable for the intended calibration process. Instead, it was proposed to design and manufacture a custom support that holds the devices at a 45° inclination, aligned with the direction of excitation imposed by the actuator, as shown in Figure 5 (right). This approach ensures that the smartwatch experiences a uniaxial excitation along its Z-axis, replicating the conditions of Method 1 and thus enabling a direct comparison between both calibration methods.

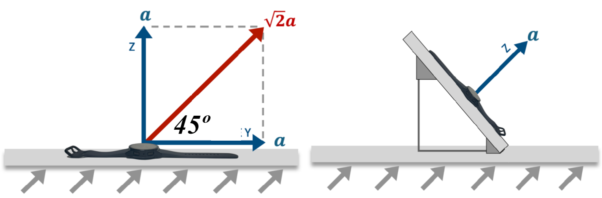

Figure 5. Smartwatch setup in Method 2. Left: horizontal plane, solution excluded from consideration; right: 45º, adopted solution.

The design of a custom fixture to support the devices must be carefully addressed, as several factors may influence the validity of the results. Among these, special attention must be given to the rigid attachment of the fixture to the vibrating platform and to the mounting of the devices on the fixture itself. Any looseness, misalignment, or insufficient clamping force could generate unwanted movements, resulting in distortion of the transmitted accelerations and, consequently, in erroneous calibration data.
Moreover, it is essential to consider that all mechanical structures subjected to dynamic excitations inevitably experience some degree of elastic deformation. If the fixture's natural frequencies fall within or close to the study's frequency range, undesired resonances may occur, potentially amplifying the input vibrations and introducing unwanted acceleration components into the measured signals. This phenomenon could significantly compromise the calibration process, leading to incorrect and unreliable estimations of the acceleration levels in the sensors.
Therefore, to mitigate this risk, it is necessary to ensure that the fixture behaves as a rigid body within the working frequency range, without exhibiting local modes or flexural deformations. To address these concerns, a modal analysis of the fixture was performed. The results revealed that the first resonance frequency is located at 56 Hz (Figure 6), which is above the operational frequency range of interest, since the calibration tests do not exceed 10 Hz. Based on these findings, it can be concluded that no significant resonances that could compromise the accuracy of the calibration results are present within the working interval.

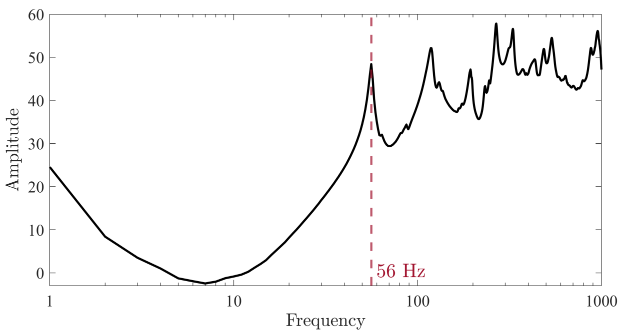

Figure 6. Fixture's global frequency response.

Regardless of the calibration method employed, since the comparative methodology is followed, a reference accelerometer was mounted onto the structure where the devices under evaluation were placed. This setup ensures that both the smartwatches and the reference sensor are exposed to the identical mechanical vibration signal.

2.3 Calibration procedure

In accordance with ISO 8041:2007 [12], for the calibration of hand-arm vibration measuring systems, each test had a duration of 30 seconds. This period was extended as needed to ensure that the excitation source reached a steady-state condition. To guarantee the validity and reproducibility of

the results, three measurements were performed for every combination of frequency and amplitude assessed. Following the sampling plans, Method 1 involved a total of 13 tests, while Method 2 consisted of only 9 tests.
The input signal was adjusted according to the specific test being conducted, with the frequency and amplitude modified as needed to align accurately with the defined sampling plan. This adjustment ensured that the reference accelerometer recorded root mean square (RMS) values of 1 m/s², 2.5 m/s², and 4 m/s², with the signals filtered through a second-order Butterworth bandpass filter.

2.4 Data processing

After completing the tests, the data recorded by the sensors were processed using an identical procedure for both calibration methods, thereby ensuring the comparability of the results. This step involved filtering the raw data from the Z-axis, which is critical to isolate the frequency range of interest and eliminate any unwanted noise that could distort the vibration signal. The filtering was performed using the same filter settings as applied to the reference accelerometer during the tests; specifically, a second-order Butterworth bandpass filter with a one-third octave bandwidth, centered on the relevant frequency band for each specific test.
In addition to removing noise from the source and the measurement environment, filtering also eliminates the effect of gravity. The accelerometer measures the sum of all forces acting on the sensor, which includes both the acceleration due to movement and due to gravity (a low-frequency signal, below 0.5 Hz, that is nearly constant). To focus specifically on the motion-induced data, it is necessary to filter out this low-frequency component.
Figure 7 presents an example of the signal recorded by the accelerometer of a smartwatch during a 1 Hz and 1 m/s² test, both before and following the filtering process.

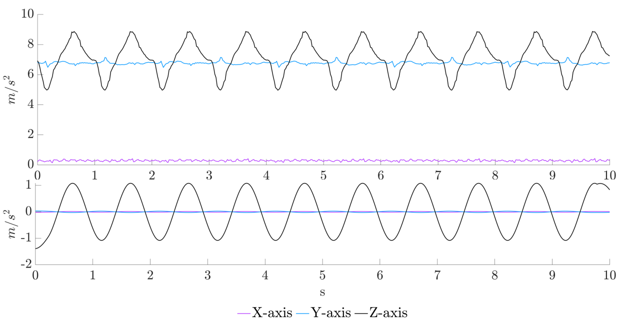

Figure 7. Signal captured by the smartwatch in a 1 Hz and 1 m/s² test. Top: before filtering; Bottom: after filtering.

Following the filtering process, the RMS value, which reflects the total energy of the input signal over a defined period, was calculated. The primary parameter under evaluation during the data processing phase is the error, which quantifies the deviation between the measurements from the test devices and the reference accelerometer.

3. RESULTS

A comparative analysis was performed to evaluate the results obtained with both calibration methods. This comparison considered the RMS values recorded by the smartwatches and their deviations relative to the reference accelerometer, which, during the tests conducted, recorded RMS-filtered accelerations of 1 m/s², 2.5 m/s², and 4 m/s².
Figure 8 presents the frequency and amplitude response of the smartwatches using calibration Method 1. The results indicate that, for all tests conducted, the values recorded by the accelerometers of the four smartwatches are almost identical. This consistency demonstrates that the devices are responding similarly to the applied vibrations. Furthermore, the measurements obtained from the smartwatches align with the recorded values from the reference accelerometer, demonstrating a high level of accuracy.

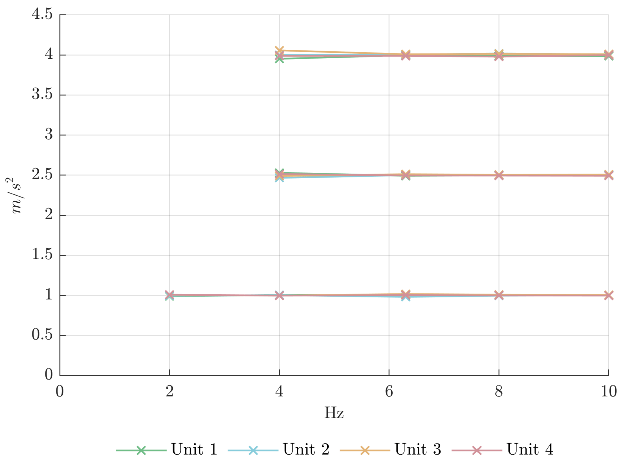

Figure 8. RMS values recorded by the smartwatches in Method 1.

Figure 9 presents the frequency and amplitude response obtained in Method 2. In contrast to Method 1, these results show some differences between the devices tested. The most significant discrepancies between smartwatches in Method 2 are observed when the input signal amplitude is 2.5 m/s², with deviations reaching up to 0.14 m/s². In comparison, the maximum deviation recorded across all tests in Method 1 was notably lower, 0.06 m/s². This demonstrates that, despite using the same devices, their accelerometers respond differently depending on the applied calibration methodology. These differences suggest that the reliability of the measurements depends not only on the smartwatch hardware but also on the calibration method employed, which may contribute to additional variability and impact the overall validity of the collected data.

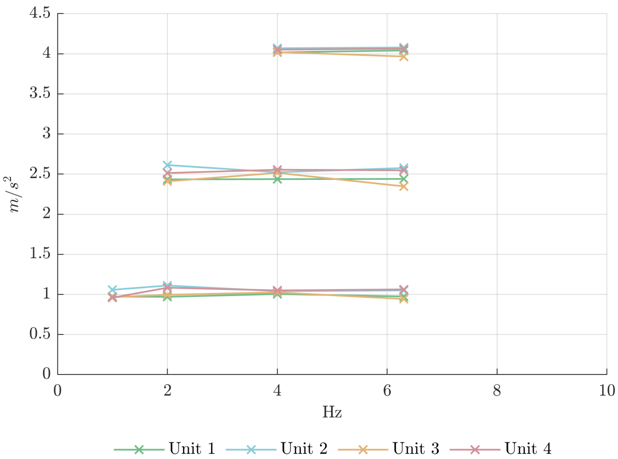

Figure 9. RMS values recorded by the smartwatches in Method 2.

According to ISO 8041:2007 [12], a smartwatch can be used for monitoring human movement and measuring hand-arm vibrations only if its frequency and amplitude response deviation remains within defined limits. These thresholds are defined as percentage-based limits, meaning that higher input amplitudes allow for a greater margin of error. They are set at 0.06 m/s² for an input of 1 m/s²; 0.15 m/s² for 2.5 m/s²; and 0.24 m/s² for an excitation of 4 m/s². Tables 1 through 4 present the absolute deviations of smartwatches relative to the reference sensor. Tests exceeding the limits defined by the standard are highlighted in red for clarity.

In Method 1, all smartwatches fully complied with the required specifications, showing deviations significantly below the established limits. The most notable discrepancies occurred with an input excitation of 4 m/s² at 4 Hz, with deviations of 0.05 m/s² in unit 1 and 0.06 m/s² in unit 3. However, these values fall well within the 0.24 m/s² limit and do not present any significant issue.

In most conducted, the deviations between the smartwatches and the reference sensor remained below 0.01 m/s², which corresponds to an error of less than 1% for all three input amplitudes. These results clearly demonstrate the high level of consistency and accuracy achieved by calibration Method 1 for hand-arm vibration measurements.

Focusing on Method 2, the deviations relative to the reference sensor remained within the permissible error margin in almost all cases, with only two exceptions. For the excitation of 1 m/s² at 2 Hz, units 2 and 4 showed errors of 0.09 m/s² and 0.08 m/s², respectively, slightly exceeding the 0.06 m/s² limit. However, considering that, using this method, a total of 36 tests were conducted across 4 smartwatches, and only 2 tests exceeded the established limit (representing less than 6% of the total tests), these discrepancies can be regarded as isolated incidents. Therefore, they do not compromise the overall reliability or effectiveness of the proposed method.

A comparison of the deviations between methods shows that, in most cases, the error is slightly greater in Method 2. This suggests that, while Method 2 provides reliable results, there is still potential to refine the methodology and achieve the level of accuracy demonstrated by Method 1.

Table 1. Absolute deviations of unit 1 relative to the reference sensor.

	1 m/s²		2,5 m/s²		4 m/s²	
	Method 1	**Method 2**	**Method 1**	**Method 2**	**Method 1**	**Method 2**
1 Hz		0,03				
2 Hz	0,01	0,03		0,07		
4 Hz	0,01	0,00	0,03	0,06	0,05	0,02
6,3 Hz	0,00	0,03	0,01	0,06	0,00	0,04
8 Hz	0,00		0,00		0,01	
10 Hz	0,00		0,00		0,01	

Table 2. Absolute deviations of unit 2 relative to the reference sensor.

	1 m/s²		2,5 m/s²		4 m/s²	
	Method 1	**Method 2**	**Method 1**	**Method 2**	**Method 1**	**Method 2**
1 Hz		0,06				
2 Hz	0,00	0,09		0,11		
4 Hz	0,00	0,04	0,03	0,02	0,00	0,07
6,3 Hz	0,02	0,05	0,00	0,08	0,00	0,08
8 Hz	0,00		0,00		0,02	
10 Hz	0,00		0,00		0,01	

Table 3. Absolute deviations of unit 3 relative to the reference sensor.

	1 m/s²		2,5 m/s²		4 m/s²	
	Method 1	**Method 2**	**Method 1**	**Method 2**	**Method 1**	**Method 2**
1 Hz		0,03				
2 Hz	0,01	0,00		0,09		
4 Hz	0,00	0,02	0,01	0,02	0,06	0,02
6,3 Hz	0,02	0,05	0,01	0,14	0,01	0,03
8 Hz	0,01		0,00		0,01	
10 Hz	0,00		0,01		0,01	

Table 4. Absolute deviations of unit 4 relative to the reference sensor.

	1 m/s²		2,5 m/s²		4 m/s²	
	Method 1	**Method 2**	**Method 1**	**Method 2**	**Method 1**	**Method 2**
1 Hz		0,04				
2 Hz	0,01	0,08		0,01		
4 Hz	0,00	0,05	0,01	0,05	0,01	0,05
6,3 Hz	0,00	0,06	0,00	0,05	0,01	0,06
8 Hz	0,00		0,01		0,02	
10 Hz	0,00		0,01		0,00	

4. DISCUSSION

This study assesses the performance of smartwatch accelerometers subjected to two distinct calibration procedures. The following analysis reviews the main results and identifies factors that may have contributed to any variations observed between the two methods.

The response obtained from the four smartwatches using Method 1 indicates that the deviations are minimal and can be considered negligible. This suggests that the behavior of the devices is highly precise and reliable within the tested frequency and amplitude range. Consequently, the devices do not introduce significant errors in their measurements relative to the excitations they are exposed to.

It is important to emphasize that Method 1 was validated in [5], thereby establishing it as the reference method for this study. Consequently, the outcomes derived from this approach are considered both reliable and accurate.

When analyzing Method 2, the deviations obtained by the tested devices are noticeably larger compared to those in Method 1. As concluded in the validated reference method, the performance of the smartwatches closely mirrors that of the reference accelerometer. Therefore, the errors observed in Method 2 are not attributable to the smartwatches' behavior itself. Instead, these discrepancies are more likely the result of errors inherent in the calibration process of this method. This suggests that improvements in the calibration procedure are necessary for Method 2 to achieve accuracy comparable to Method 1.

The differences observed in Method 2 can largely be attributed to the mounting procedure. Despite efforts to secure the devices as firmly as possible, the fixation method used was relatively rudimentary. This approach may have resulted in imperfect attachment of some smartwatches, causing slight displacements during the measurement process. These movements could have occurred not only along the Z-axis but also along the other two axes that were not considered in the analysis. These uncontrolled shifts in position may explain the variations in error observed among the different smartwatches, with some exhibiting more significant deviations related to the reference sensor.

The limitations associated with the manual fixation method suggest that a more precise, automated mounting system would be beneficial in future experiments to minimize these sources of error and improve the reliability of the results.

In addition to the calibration methodologies and mounting procedures, environmental factors could have also contributed to the observed variations between the two methods. Fluctuations in temperature and relative humidity, as well as vibrations in the surrounding environment may have influenced the measurements, particularly in Method 2, where the manual fixation may have been more susceptible to external disturbances. Future studies could address this by conducting tests in more controlled environments, where these factors are continuously monitored and regulated.

5. CONCLUSIONS

Smartwatches are increasingly utilized in applications such as healthcare or occupational risk assessment, where precision and reliability of data are critical. Consequently, a deeper understanding of the behavior of their inertial sensors is essential to accurately interpret the data they generate. For this purpose, this study presents a comparative analysis of two calibration methods used to characterize the frequency and amplitude response of the accelerometers embedded in four smartwatches of the same model.

Method 1 used a uniaxial vibration bench, which allows for individual sensor characterization, while Method 2 used a vibration platform that generates vibrations on a surface, allowing the simultaneous evaluation of multiple sensors. Method 1, previously validated, was established as the reference for evaluating sensor performance. As the goal is to calibrate multiple devices in the shortest time, this study, along with future research, focuses on refining Method 2 based on the comparison with Method 1.

In this research, only the Z-axis was analyzed. However, once the calibration method is optimized, the procedure should be extended to evaluate all three axes of the triaxial sensor, in order to fully characterize the smartwatch for acceleration measurement applications.

Since these smartwatches are used for collecting data related to human movement, it is essential to characterize their accelerometers within the amplitude and frequency ranges typical for these activities. These ranges include amplitudes up to 4 m/s^2 and frequencies up to 10 Hz. However, each calibration method has its own limitations in terms of excitation sources. Method 1 enables high-amplitude excitation at higher frequencies but is more restricted at lower frequencies. In contrast, Method 2 can generate larger excitation amplitudes at lower frequencies, but it is less effective at reaching higher frequencies.

The results from Method 1 showed that the smartwatches exhibited minimal deviations relative to the reference sensor, demonstrating their precise behavior under vibratory excitations. This suggests that the smartwatches' accelerometers can provide reliable measurements within the tested frequency and amplitude ranges, supporting their potential for high-precision human motion analysis.

Method 2 revealed larger deviations from the reference method, primarily due to limitations in the calibration process. These discrepancies are not attributed to inherent issues with the smartwatches' sensors but are likely caused by the mounting procedure. The manual fixation of the devices may have caused uncontrolled movements during measurements, which contributed to the observed errors.

While these unwanted displacements did not significantly impact the overall accuracy and reliability of the method, they highlight the need for a more robust and automated mounting system to enhance the consistency of results. In future studies employing this calibration method, a more controlled mounting procedure will be adopted to minimize uncertainties and guarantee more repeatable measurements.

Additionally, environmental factors, such as temperature and vibrations, may also influence sensor performance and should be carefully considered in future evaluations.

In summary, the precise calibration of smartwatch accelerometers is crucial for their reliable application in human movement analysis and related fields. This study highlights the need to select a calibration method that optimizes both accuracy and efficiency. Future work will focus on refining the accelerometer characterization procedure to minimize uncertainties and, thereby, improve the reliability of inertial sensor measurements.

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