

# Gait Assessment using Microwave Radars mounted on Standard Walker

Octavian Postolache

Iscte - Instituto Universitario de Lisboa  
and Instituto de Telecomunicacoes  
Lisbon, Portugal  
opostolache@lx.it.pt

Vitor Viegas

Escola Naval, University of Lisbon and  
Instituto de Telecomunicacoes  
Lisbon, Portugal  
vitor.viegas@escolanaval.pt

José Miguel Dias Pereira

Escola Superior de Tecnologia de  
Setubal and Instituto de  
Telecomunicações  
Lisbon, Portugal  
dias.pereira@estsetubal.ips.pt

**Abstract**—Gait rehabilitation is a complex process considering the complexity of movement that involves different parts of the human body. To assure the safety of the rehabilitation process walking aids are a common indication in clinics, the standard walker being one of the most prescribed taking into account its stability. Embedding sensors on the level of the walker can provide additional capabilities associated with gait monitoring that may be used to evaluate the user gait rehabilitation outcome. Sensing user motion during walker usage can be also used to avoid wrong usage that can conduct to falls. In the current study a standard walker with two Microwave Doppler radars was implemented to extract information on user gait during the rehabilitation process as well as information about the sequence of the standard walker usage. The signals acquired from the measurement channels were considered for time-frequency analysis, including features extraction such as mean instantaneous frequency (MIF) and mean instantaneous bandwidth (MIB) to characterize normal and abnormal gait. The capabilities of time-frequency analysis methods as the starting point on gait classification is also considered.

**Keywords**—gait rehabilitation, walking aid, motion sensing, gait analysis, time frequency analysis

## I. INTRODUCTION

The ageing phenomenon is nowadays a reality, and in this context, the prevalence of motor disabilities and the motor rehabilitation, particularly among the elderly population, are increasing the healthcare costs. The recent advances in medicine particularly in physical rehabilitation assures new services in this field for better quality of life for this group of people. One of the critical events that lead to impairment requiring a long recovery period based on physical rehabilitation are the falls. Furthermore, falls are major cause of morbidity among elders [1]. Fall risks are associated to changes in gait characteristics such as decreasing speed, stride frequency, and stride length [2]. To prevent falls the walking aids present a common solution. According to the level that gait is affected, several walker models are commonly used in rehabilitation clinics and at home. The usage of walkers is reported in the literature not only for walking safety of the users, but also during rehabilitation to prevent undesired falls [3][4]. A standard walker helps the users to stay balanced by providing a wide base of support when the right type of walker is selected. The standard walker is more stable and it is not characterized by wheels being in general used for people with gait impairments. The two-wheel walker [5] allows users to place weight on the walker, the legs with wheels allow the user to easily push the walker forward, and the legs without wheels prevent the walker from rolling while the user is stepping forward. For users who are relatively healthy and possess good balance, a four-wheel walker solution is considered when the walker is not primarily utilised for balance support. [6]. As an equipment associated with gait rehabilitation

the walker proves to improve confidence and restore or maintain motor ability at the highest possible level avoiding falls during the training period. The question is related to the usage of walker that can affect gait rehabilitation duration for reduced rehabilitation outcomes. In this context can be mentioned a study published by the Vogt et al. [7] showed that rollator assistance does not interfere with rehabilitation outcome and in some cases may be very useful to decrease the rehabilitation periods.

To improve the evaluation process, instrumented walkers were developed by Postolache team but also are reported in the literature by other authors, R. A. Bachschmidt et al. [8]. They presented a walker with force sensing during gait based on strain gauges with capabilities on balance estimation and hand loads. In the same field, of adding force sensor usage as well as IMUs is reported by Viegas et al. [9]. Various solutions for sensing user gait are presented in the literature based on different types of contact sensors as well as remote sensing. In the latter category can be mentioned the implementations using microwave radars.

Seifert et. al. reported the usage of continuous wave radar to extract gait parameters from subjects walking on a treadmill using advanced signal processing algorithms to separate Doppler frequency envelope of the toe, ankle, and knee [10]. Experimental setups for gait capture and validation of Doppler radar solutions are presented by L. Wang et al. [11], focusing on the study of gait in users that are walking on treadmill, where data coming from Vicon and Doppler radar sensing systems are processed in a laboratory setting.

An important contribution in the field of the usage of frequency modulated continuous wave (FMCW) doppler radar for gait characterization and gait abnormalities detection is given by Rahman et al. [12]. The gait dynamics in terms of step-time variability is considered in their paper and the accuracy of the RF measurements is validated by comparing them with gold standards. The used Short Time Fourier Transform (STFT) prove to be limited considering other time-frequency transforms such as Wigner-Ville distribution.

Seifert et al. on [13] proposed innovative methods to identify changes in gait patterns based on radar micro-Doppler signatures for gait recognition. Micro-Doppler signatures and the short-time energy signal of the radar return are extracted from a noise-reduced spectrogram based on an adaptive thresholding technique proposed in [14].

The paper presents the following organization: In section II are presented the smart walker architecture and walker hardware components. Section III focusses on digital signal processing and time frequency analysis. Section IV presents the experimental validation results and a discussion, followed by Section V, which highlights the conclusions and future work.

## II. SYSTEM DESCRIPTION

Walking aids may be considered as part of walking aid network that can be used in physical rehabilitation clinics as is reported in [5]. Regarding the motion requirements, walking aids require short range wireless communication capabilities, such as those provided by Bluetooth or Wi-Fi. Taking into account the required number of walkers to be used at the same time for rehabilitation in clinics, Bluetooth wireless communication was considered appropriate. The general architecture of the proposed system, featuring a smart standard walker with Bluetooth communication capabilities, is presented in Fig. 1.



Fig. 1. Smart Standard Walker Gait Monitoring Architecture.

The main elements of the smart standard walker are the motion sensors, the acquisition and wireless communication platform, and the advanced digital signal processing and analysis unit, materialized by a cloud computing platform or a local server.

### A. Motion Sensors

Lower limb motion monitoring was carried out using microwave Doppler radar sensing technologies that assure the transmission of a continuous low-energy microwave radiation signal at a target area, providing also a signal associated with RF reflected waves. In the present case, a FMCW Doppler radar (IVS-162 DRS) was used to gather data on the gait of standard walker users. Taking into account the full beam width (azimuth horizontal  $45^\circ$  elevation vertical  $38^\circ$ ) that characterize the chosen sensor and the necessity to individually sense the user lower limb, two Doppler radar sensors were considered. A block diagram of the Doppler radar sensor that was used and the Doppler radar experimental setup on the standard walker are presented in Fig. 2. In the present setup the distance between two radars was 5 cm.

The two microwave Doppler radars (DRad1, DRad2) are fixed on the standard walker to capture the legs motion (Fig. 3). The receiving antenna connected to low noise amplifier (LNA). Two mixers, M1 and M2, are used on demodulation of the received signals by the received antennas (RX\_ant1, RX\_ant2). The radars provide the intermediate frequency (IF) signals as output, which are acquired and processed to extract patterns of lower limb motion. According with the motion speed several sampling rates were considered.

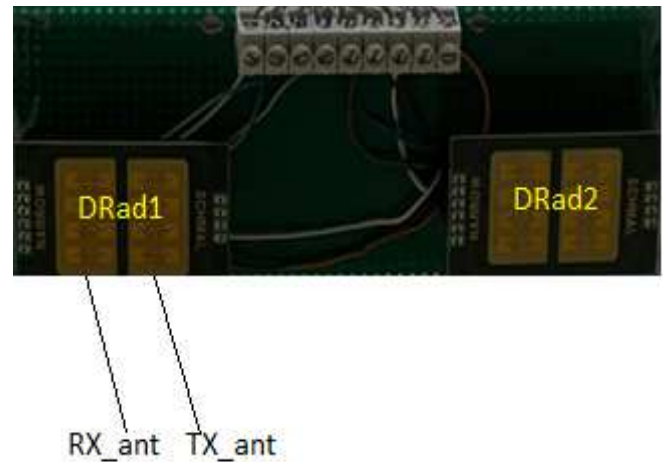
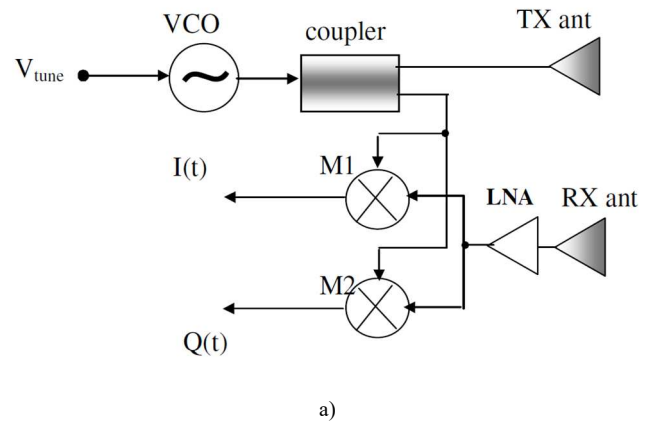


Fig. 2. Motion sensor: a) block diagram; b) experimental setup.

The motion radar includes a K-Band VCO-transceiver that is voltage controlled via  $V_{tune}$ . The radar assures 24 GHz to 24.25 GHz transmission frequency according to the applied  $V_{tune}$  voltage (constant or sawtooth wave). To simplify the system regarding signal generation, in the present case both radars are powered at 5V, with  $V_{tune} = 5$  V. The signal coming from the receiving antenna is demodulated, and a set of two intermediate frequency signals (direct signal (I), quadrature signal (Q)) is obtained for each radar. In the present case, the direct signals acquired from DRad1 and DRad2 are being used to extract data on the gait of the volunteer that is using standard walker.

### B. Acquisition and Communication

The Doppler radars' direct signals ( $I_1$ ,  $I_2$ ) are applied to the analog inputs of the Shimmer 3 that is characterized by MSP 430 microcontroller (24 MHz, 16 Bit), Bluetooth RN42, Integrated 8 GB microSD card. Shimmer 3 LabVIEW driver was used on the development of LabVIEW software that was developed to provide acquisition and Bluetooth communication control. The acquisition rate was 200 S/s and 400 S/s for both Doppler radars mounted on the standard walker.



Fig. 3. Smart Standard Walker Prototype including two microwave radars (DRad1 and DRad2) and acquisition and communication platform (AqCP).

### III. LOWER LIMB MOTION SIGNAL PROCESSING

During rehabilitation the gait as well as the sequence check of the standard walker is monitored through the signals provided by the radars on motion of swinging legs. The swinging of torso and arms typically associated with independently walking gait (without standard walker support) was not considered. The deployment of the radars allows for independent exposure of each leg to the transmission radar waves during short distance walker usage. Unusual usage of the walker can be also detected through the analysis of the acquired radar signals.

#### A. Doppler Radar Signals

The acquired radars signals associated with the two Doppler radars (DRad1 and DRad2) mounted on the standard walker are presented in Fig. 4. The acquired signals are affected by a radar DC component that is estimated after acquisition when no motion conditions are applied. For the Doppler radar pairs mounted on the walker the obtained DC values are  $VDRad1 = 1.72$  V and  $VDRad2 = 2.12$  V that were subtracted from the acquired signals from DRad1 and DRad2 channels.

The reflected waves by the lower limbs during the normal and abnormal gait can be used to extract the information about the legs velocities or anomalous gait occurrence. At the same time other gait metrics associated with standard walker usage can be extracted through the digital signal processing of Doppler radar acquired signals.

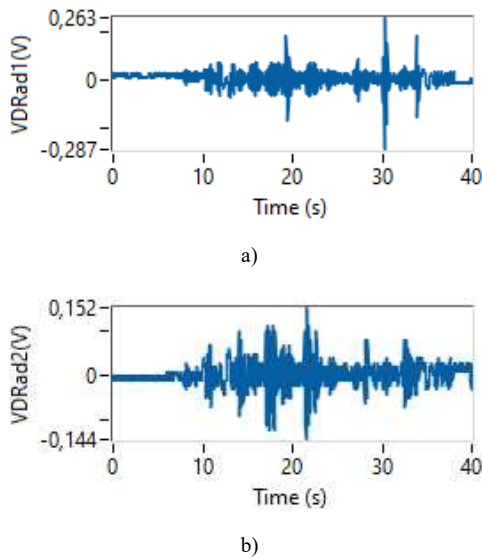


Fig. 4. Doppler radar Signals evolution during regular gait of the users that are using the standard walker: a) signal acquired by DRad1 (left side); b) signal acquired by DRad2 (right side).

#### B. Time Frequency Analysis of Doppler Radar Signals

The time frequency analysis (TFA) of the acquired doppler radar signals is a method for identifying gait patterns associated with normal or abnormal gait. Two types of TFA and associated features, mean instantaneous frequency and mean instantaneous bandwidth, were considered in this study.

The Short Time Fourier Transform (STFT) and Wigner Ville Distribution (WVD) methods have been used for time-frequency representation, defined as follows:

$$STFT(t, f) = \int_{-\infty}^{\infty} rad_i(t + \tau)w(\tau) \cdot e^{-j2\pi f\tau} d\tau \quad (1)$$

where  $t$  is time,  $f$  is frequency,  $rad_i$  is the acquired radar signal and  $w$  is a sliding window function.

$$WVD(t, \omega) = \int_{-\infty}^{\infty} R_{\tau}(t, \tau)e^{-j\omega\tau} d\tau \quad (2)$$

where  $R_{\tau}(t, \tau)$  is the time-dependent autocorrelation of the signal  $rad_i(t)$ ,  $i = \{1,2\}$  - two radars are used, defined by the following equation:

$$R_{\tau}(t, \tau) = rad_i\left(t + \frac{\tau}{2}\right)rad_i^*\left(t - \frac{\tau}{2}\right) \quad (3)$$

The STFT and WVD are used considering time-frequency resolution requirements.

Analyzing the STFT and WVD spectrograms reveals the existence of gait signatures indicated by the power distribution related to the lower limb motion. Anomalous gait can be highlighted by spectrogram power distribution. At the same time the spectrogram analysis can provide information about patient gait rehabilitation outcome during the usage of the smart standard walker.

#### C. Gait Parameters and TFA

Several gait parameters such as gait velocities can be extracted based on spectrogram-based analysis. According with [15] the lower limbs velocities estimation corresponds to the frequency shift with the highest reflected RF wave that are captured by the received antenna (RX\_ant1, RX\_ant2 in the present case). Features of time frequency analysis are later considered to characterize the type of the gait.

Based on the calculated features effectively highlight the tendency towards normal or abnormal gait and can be used for future patient rehabilitation outcome evaluation during the gait rehabilitation process. The features are calculated based on time frequency analysis and are expressed by mean instantaneous frequency (MIF) and mean instantaneous bandwidth (MIB). In the present study the MIF was used as defined by:

$$f_{mc} = \frac{\int_0^{\infty} fP(t, f)df}{\int_0^{\infty} P(t, f)df} \quad (4)$$

where  $P(t, f)$  represents the spectrogram, and mean instantaneous bandwidth is defined by:

$$\Delta f_{mc} = \sqrt{\frac{\int_0^{\infty} (f - f_{mc})^2 P(f)df}{\int_0^{\infty} P(f)df}} \quad (5)$$

### IV. RESULTS AND DISCUSSIONS

An experimental protocol was carried out to evaluate the smart walker capabilities considering the gait remote sensing based on two microwave Doppler radar mounted in the standard walker. Different tests were carried out with the

participation of healthy volunteers that simulated normal and abnormal gait during walker usage. Other conditions were also considered during the experimental validation of the system such as different walking speeds (slow, regular, fast). The tests were carried out for an imposed period of training time or for an imposed distance (e.g. 4 m) of standard walker usage. The digital data delivered by acquisition and wireless communication platform (AqCP) were stored to be later analyzed using time-frequency transforms such as STFT and Wigner Ville Distribution. Based on the spectrogram's analysis, time frequency features such as MIF are calculated for regular and abnormal gait (left side impaired or right side impaired).

### A. Gait Spectrograms

The time frequency analysis of the recorded signals (Fig. 4) from the smart standard walker was initially employed to derive a set of gait characteristics. Currently, the number of steps and velocity are being used instead; however, time frequency analysis is reported as the recommended standard method for gait analysis using microwave radars in the literature [12]. Therefore, two types of spectrograms were calculated using STFT and WVD for lower limb reflected waves during normal and anomalous walking supported by the walking aid.

For regular gait, the acquired signals from both microwave radars were processed using STFT with a Hamming window and 64 window length. Fig. 5 presents the power distribution of the reflected signals during the walking test with the smart standard walker. Taking into account the time-frequency resolution requirements time frequency analysis based on Wigner-Ville Distribution was applied. In Fig. 6 are presented the VVD spectrograms for user regular gait using a standard walker.

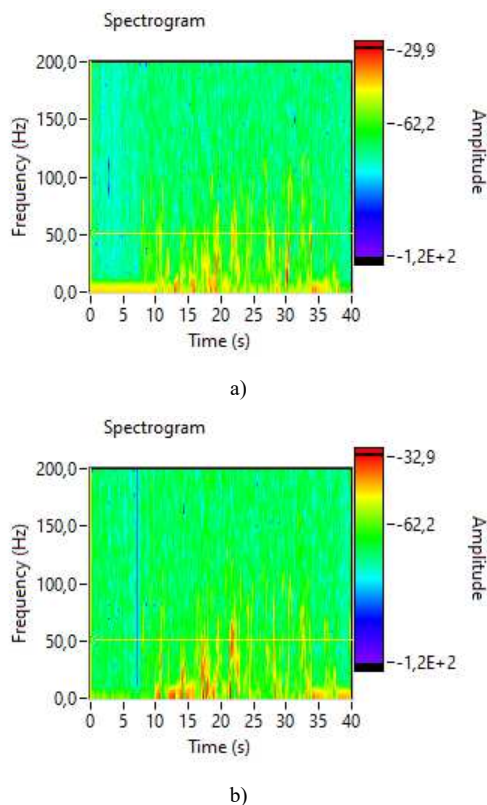


Fig. 5. The evolution of STFT of the Doppler Radar Signals during regular gait supported by standard walker: a) STFT associated with DRad1 signal - left side; b) STFT associated with DRad2 signal - right side.

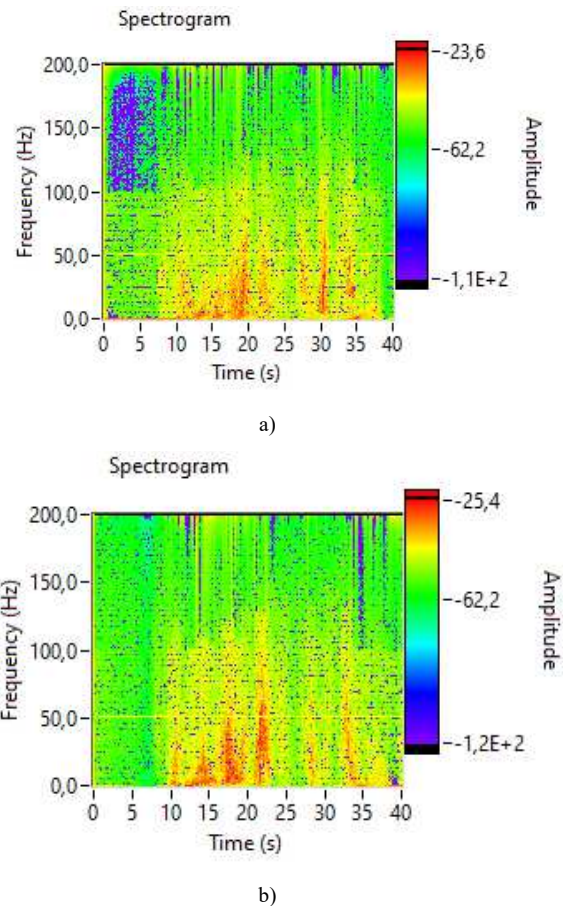


Fig. 6. The evolution of WVD of the doppler radar signals during regular gait supported by standard walker: a) STFT associated with DRad1 signal - left side; b) STFT associated with DRad2 signal - right side.

Comparing the WVD obtained spectrograms, it is noticeable that the walking steps that are distinctly represented in the spectrogram level as a sequence of higher reflected power. At the same time can be observed a higher variability regarding the reflected power at different frequencies in DRad1 and DRad2 spectrograms.

For the anomalous gait associated with impaired lower limbs (left or right), several 4m distance walking tests were carried out followed by time frequency analysis. In Fig. 7 and Fig. 8 are presented the WVD spectrograms obtained for the case of anomalous gait (left-side impaired).

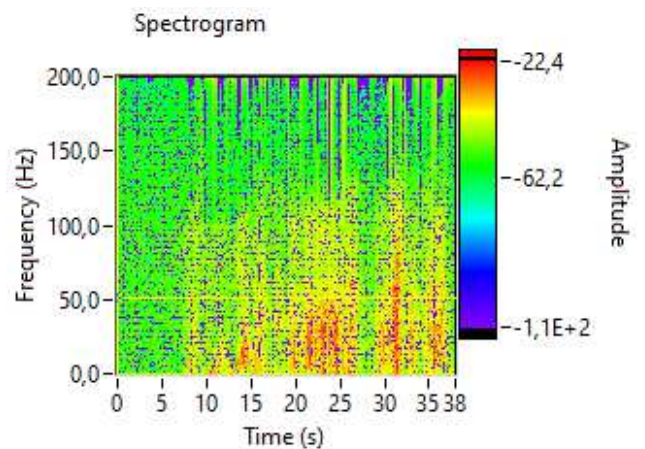


Fig. 7. The evolution of WVD of the Doppler Radar Signals (DRad1 signal – mounted on left side of the walker) during impaired left side gait supported by standard walker.

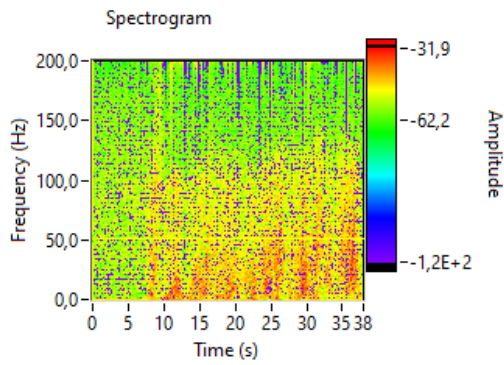


Fig. 8. The evolution of WVD of the Doppler Radar Signals (DRad2 signal – mounted on right side of the walker) during impaired left side gait supported by standard walker.

When comparing the VWD obtained for regular and anomalous gait, it can be observed different patterns of power distribution for different values of frequencies, which can be a starting point for regular and anomalous gait classification. Additionally, spectrogram specific features, MIF (mean instantaneous frequency) were evaluated for regular and anomalous gait.

### B. Features of Gait Spectrogram

The MIF features are calculated for WVD spectrograms of the acquired radar signals. The impaired left and right side anomalous walking gait were analyzed in comparison to regular gait. In Fig. 9 are presented the MIF evolution for the WVD spectrograms corresponding to DRad1 impaired left side anomalous gait.

The MIF analysis underlines the difference between regular gait and anomalous gait when and imposed threshold of 100 Hz is imposed. In the case of anomalous gait, the MIF peaks are mostly below the imposed limit. For the regular and left side impairment, the MIF evolution based on DRad2 (mounted on the walker right side) is presented in Fig. 10.

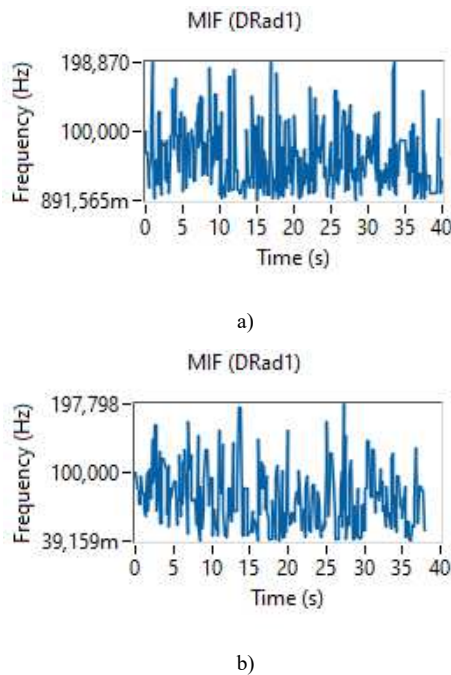


Fig. 9. The evolution of MIF for DRad1 signal – mounted on left side of the walker for: a) regular gait; b) impaired left gait supported by standard walker.

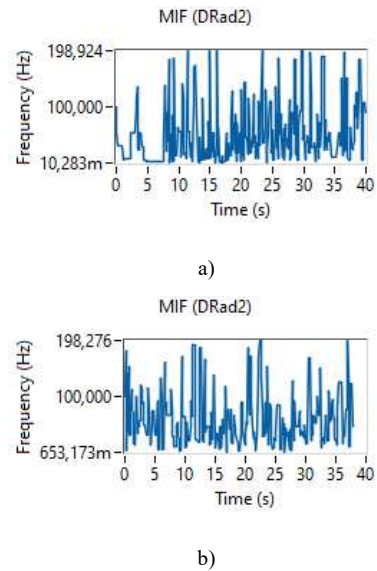


Fig. 10. The evolution of MIF for DRad2 signal – mounted on right side of the walker for: a) regular gait; b) impaired left gait supported by standard walker.

The MIF analysis underlines the different evolutions based on a 100Hz threshold. The DRad2 anomalous gait figures show that majority of the values are below 100Hz by comparison with regular gait.

Additionally, a Bland-Altman plot is used to analyze the MIF values distribution for regular and anomalous gait, calculated from the WVD spectrograms obtained for the DRad1 and DRad2 acquired signals. When analysing the Bland-Altman plot, can be underlined the higher concentration of the values in 2 to -2 interval in the case of anomalous gait (left or right side impairment), while the regular gait is characterized by higher dispersion. This observation is also supported by histograms that were conceived based on Bland-Altman plot values. In Fig. 12 are presented the histograms associated with Bland-Altman plots of Fig. 11.

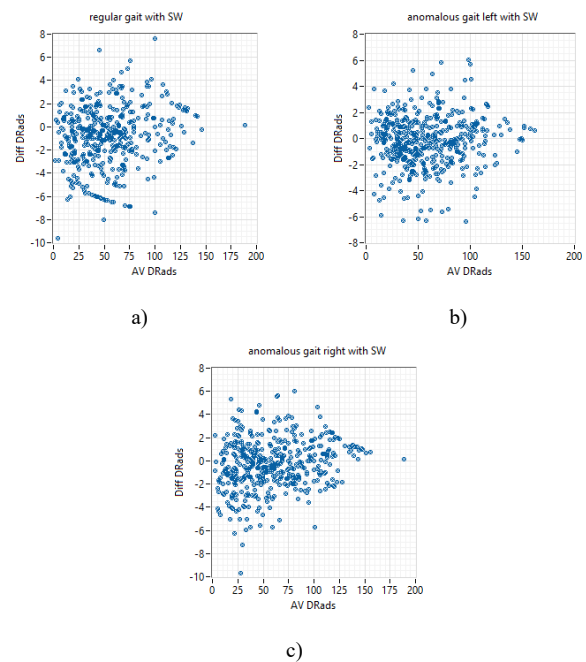


Fig. 11. The Bland-Altman plot of MIF associated with DRad1 and DRad2 signals for different gait conditions: a) regular gait; b) impaired left gait; c) impaired right gait supported by standard walker.

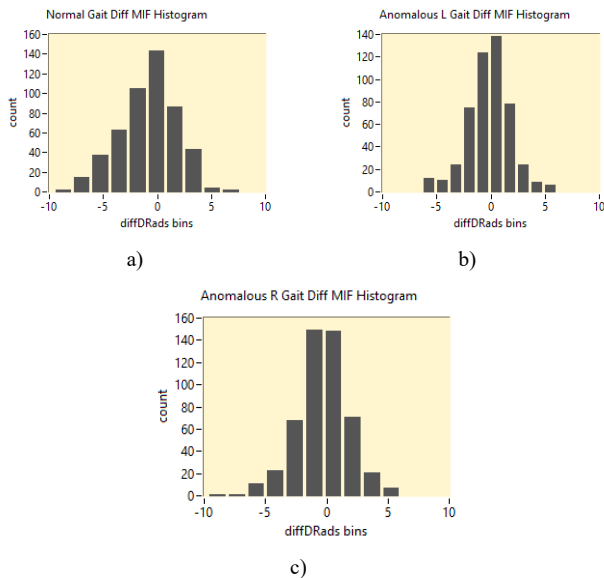


Fig. 12. The histograms of the Bland-Altman plot values for different gait conditions: a) regular gait; b) impaired gait – left side; c) impaired gait-right side for a standard walker user.

The histograms clearly underline the concentration of different values obtained from DRad1 and DRad2 in the  $[-2;2]$  interval, while a wider distribution of the values can be observed for anomalous gait. This can be a very useful observation and can be used as metric for diagnosing regular or abnormal gait. At the same time, it is a measure of gait rehabilitation outcome, that can be used for the physiotherapists in order to quantify gait improvement for the standard walker users.

## V. CONCLUSIONS

The designed and implemented standard walker with gait pattern sensing capabilities was validated for different gait conditions simulated by healthy users including regular, impaired left side and impaired right-side gait. The developed sensing unit including the FMCW Doppler radars, signal conditioning and acquisition and communication unit based on Shimmer 3 can be used for other models of standard walker, or on two wheels or four wheels walkers.

Regarding the signal analysis, the usage of Wigner Ville Distribution and MIF features proved to be a solution to discriminate between the regular and abnormal gait. Based on the Blant-Altman diagrams of MIF and histograms were clearly highlighted differences between regular and abnormal gait, and can be considered a simple way to classify the gait.

As future work can be considered the development of advanced classifiers based on artificial intelligence, such as 2D deep learning classifiers associated with WVD spectrograms and MIF and MIB features calculated for the signals coming from the radars.

## ACKNOWLEDGMENT

This work was funded by the Instituto de Telecomunicações and FCT/MCTES through national funds and, when applicable, from EU funds co-financed under the UIDB/50008/2020 project. The work as also supported by Master of Managing Digital Transformation in the Health Sector – ManagDiTH funded by EU/DIGITAL.

## REFERENCES

- [1] J. M. Housdorf, D. A. Rios, and H. K. Edelber, "Gait variability and fall risk in community living older adults: A 11-year prospective study," *Archives Phys. Med. Rehab*, Vol. 82, No. 8, pp. 1050–1056, 2001.
- [2] Y. Barak, R.C. Wagenaar, and K.G. Holt, "Gait characteristics of elderly people with a history falls: A dynamic approach," *Phys Therapy*, Vol. 86, No. 11, pp. 1501–1510, 2006.
- [3] O. Postolache, P. Girão, J. M. Dias Pereira, and G. Postolache, "Smart Walker for Pervasive HealthCare," *Proc. of International Conf. on Sensing Technology ICST*, Palmerston North, New Zealand, Vol. 1, pp. 1–5, December, 2011.
- [4] G. Postolache, P. M. Girão, and O. Postolache, "Applying smartphone apps to drive greater patient engagement and personalized physiotherapy," *Proc. of IEEE International Workshop on Medical Measurements and, Lisbon, Portugal*, Vol. 1, pp. 1–6, June, 2014.
- [5] O. Postolache, J. M. Pereira, V. Viegas, and P. S. Girão, "Gait Rehabilitation Assessment Based on Microwave Doppler Radars Embedded in Walkers," *Proc. of IEEE International Workshop on Medical Measurements and Applications (MEMEA)*, Italy, Vol. 1, pp. 1–6, June, 2015.
- [6] Mayo Clinic, "Tips of choosing and using walkers," on-line at: <http://www.mayoclinic.org/healthy-living/healthyaging/multimedia/walker/sls-20076469>, visualized on February, 2015.
- [7] L. Vogt, K. Lucki, M. Bach, and W. Banzer, "Rollator use and functional outcome of geriatric rehabilitation," *J Rehabil Res Dev*, Vol. 47, No. 2, pp. 151–156, 2010.
- [8] R. A. Bachschmidt, G. F. Harris, and G. G. Simoneau, "Walker-assisted gait in rehabilitation: a study of biomechanics and instrumentation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, Vol. 9, No. 1, pp. 96–105, 2002.
- [9] V. Viegas, J. M. Pereira, O. Postolache, and P. S. Girão, "Spy walker: A convenient way to assess gait in walker assistive devices," *Proc. of IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, 2018.
- [10] A. K. Seifert, M. Grimmer, and A. M. Zoubir, "Doppler Radar for the Extraction of Biomechanical Parameters in Gait Analysis," *IEEE J Biomed Health Inform*, Vol. 25, pp. 547–558, 2021.
- [11] L. Wang, Z. Ni, and B. Huang, "Extraction and Validation of Biomechanical Gait Parameters with Contactless FMCW Radar," *Sensors*, Vol. 24, No. 13, pp. 1–13, 2024.
- [12] M. Rahman, D. Martelli, and S. Z. Gurbuz, "Gait Variability Analysis with Multi-Channel FMCW Radar for Fall Risk Assessment", *Proc. of 2022 IEEE 12th Sensor Array and Multichannel Signal Processing Workshop (SAM)*, Trondheim, Norway, pp. 345–349, 20–23 June 2022.
- [13] A. Seifert, M. G. Amin, and A. Zoubir, "Toward Unobtrusive In-Home Gait Analysis Based on Radar Micro-Doppler Signatures," *IEEE Transactions on Biomedical Engineering*, Vol. 66, No. 9, pp. 2629–2640, 2019.
- [14] Y. Kim and H. Ling, "Human activity classification based on microDoppler signatures using a support vector machine", *IEEE Trans Geosci Remote Sens*, Vol. 47, No. 5, pp. 1328–1337, May 2009.
- [15] F. Wang, M. Skubic, M. Rantz, and P. E. Cuddihy, "Quantitative gait measurement with pulse-Doppler radar for passive in-home gait assessment," *IEEE Trans Biomed Eng*, Vol. 61, No. 9, pp. 2434–2443, 2014.