Gait Rehabilitation Assessment Based on Microwave Doppler Radars Embedded in Walkers

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***Abstract* - Human gait is a complex motion that implies the movement of different parts of the body such as arms, legs and feet, being the functional human movements' analysis indispensable for bio-mechanical diagnostic and treatment tool for clinics and rehabilitation services. During the rehabilitation process, walkers are frequently prescribed to improve the patient's stability but can also be transformed into instruments for quantitative evaluation of rehabilitation progress by embedding sensors to capture the motion characteristics. In this work, a practical approach concerning the possibilities to use microwave Doppler radars embedded in four wheels walkers for gait capture is presented. The signals acquired from the sensors are processed using time-frequency transform such as STFT. A set of gait characteristics, such as gait velocity and stride rate, are extracted based on wavelet signal processing, STFT spectrogram and moving average filtering. A set of spectrogram features is calculated to discriminate between normal and abnormal gait.**

Keywords *–gait rehabilitation, microwave Doppler radar, wireless instrumentation, gait analysis,*

I. INTRODUCTION

The economic developments in the second part of the 20th and 21st centuries made possible dramatic increases in life expectancy that contributed to the population aging phenomena around the world. Considering the aging phenomena the motor disabilities in elderly people are frequently, however advances in medicine and rehabilitation may contribute to maintain the quality of life for this group of people. The relation between aging and disability is not well known but some studies indicate that about 27-39% of adults with disability had the onset prior to age 44, 25 to 32% had disability onset between ages 45 to 64 years, with the remainder of onset occurring in later life [1]. Impairment groups that have seen significant increases in long-term survival include cerebral palsy, spine bifida, muscular dystrophies, spinal cord injuries, polio, and rheumatoid arthritis [2]. The entrances in these groups are frequently related to falls that are major cause of morbidity in elders [3].
The fall risks are related with changes in gait characteristics such as decreasing speed, stride frequency and stride length [4]. To prevent falls but also to help people with motor disabilities the usage of walkers represents a solution [5][6][7]. A walker helps the users to stay balanced by giving wide base of support when the right choice of walker is carried out, considering that different types of walkers are available such as no wheels, 2 wheels and four wheels walkers. If stability is a significant concern, the right solution is the standard walker without wheels the walker must pick up to move. The two-wheel walker allows the 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. If the user doesn't need to lean on the walker for balance, a four-wheel walker solution, which permits the user to walk faster, is recommended [8]. The walkers are generally used by limited elderly people as primary walking aid, however the walker usage in generalized form during rehabilitation prove to improve confidence and restore or maintain motor ability at the highest possible level. A study published by the Vogt et al. [9] showed that rollator assistance does not interfere with rehabilitation outcome and in some cases may be very useful to decrease the rehabilitation periods. In all the studied cases the used rollators were not characterized by any sensing device, no information about the characteristics of user motion being delivered to the physiotherapist. In these conditions the evaluation of user rehabilitation progress was done based on subjective evaluation and continuous scale physical functional performance [10]. To improve the evaluation process, instrumented walking aids have been developed by different research groups. Thus R. A. Bachschmidt reports [11] the development of a strain gauge-based walker instrumentation system characterized by six degree-of-freedom measurement of resultant subject hand loads. The description of upper extremity kinetics and kinematics during walker-assisted gait can be used to appropriate choice of rehabilitative strategies. Chan et al. [12] presents a smart rollator prototype that includes sensing channels for distance and speed, tri-axial acceleration monitoring, force and seat usage monitoring and also physiological parameters monitoring. In this case, the Bluetooth protocol was used to transmit the data from the sensors to a local data terminal. Referring to gait assessment for walker users, Postolache et al. presents in [5] and [6] a two wheel smart walker and a mobile application that permit to the physiotherapist to access the data from the sensors, including a microwave Doppler radar as a motion sensor. The high demand by physiotherapists for smart walker based solutions for gait rehabilitation monitoring and the recommended

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improvements obtained during demo sessions as part of EHR Physio workshops organized by the O. Postolache research team, streamlined new developments in this field that conducted to new smart walker prototypes for unobtrusive continuous gait assessment which offer great advantages regarding walking parameters changes that can be related with the fall risk. At the same time smart walker implementations may be easily integrated in s-Health architectures [13] that focus on m-Health smart cities interractions.

The article presents a walker instrumented with a microwave FMCW Doppler radar sensor array connected to an acquisition and Wi-Fi communication unit, the acquired radar signals being processed by a local processing and communication unit that is part of a client-server architecture developed for walker users remote gait assessment. Important part of the presented work is related to the Doppler radar signature processing for gait characteristics calculation and normal/abnormal gait feature extraction.

In the next section is presented the instrumented walker hardware components. Section III gives detailed description of algorithms applied to extract information about walker user gait characteristics. Section IV presents the results and discussions related to the performed tests with the implemented system with healthy volunteers' participation and we conclude in section V.

II. System Description

The frequently usage of walkers to increase the user stability during the common daily activity but also during the gait rehabilitation periods was considered as the starting point for development of an instrumented walker prototype. The measurement channels were materialized by a set of motion sensors embedded in a four wheel walker to provide information about user activity and changes in gait characteristics of walker user. An acquisition and wireless communication unit assures the integration of instrumented walkers in an ad-hoc network including a local processing, data storage and communication unit as part of a client-server architecture for walker user's assessment during the gait rehabilitation. The general architecture of the system is presented in Fig.1. The main instrumentation components of the implemented instrumented walker are following presented.

A. Motion Sensor

The FMCW Doppler (IVS-162 DRS) radar was considered as the main sensor embedded in the two wheels and four wheels walkers to capture the lower limb motion detection. The block diagram of the used motion sensor is presented in Fig. 2. The microwave Doppler radar motion sensor embedded in walker (Fig. 3) is of the frequency modulated continuous wave (FMCW) type and includes a transmission antenna and a receiving antenna connected to an I/Q receiver with low noise amplifier and the M1 and M2 mixers.

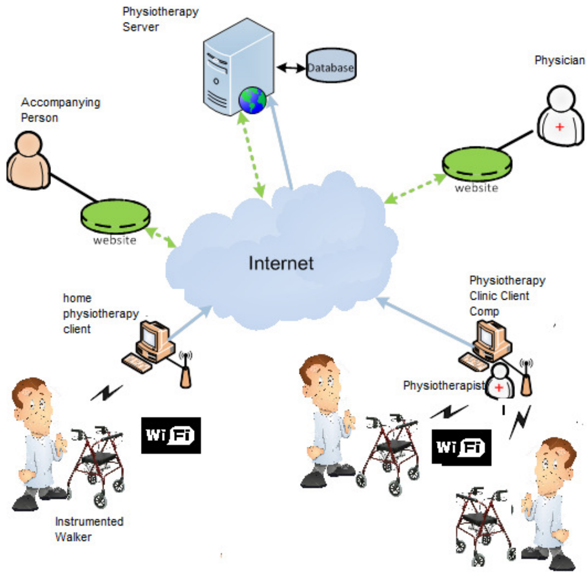


Fig. 1. Gait rehabilitation assessment client-server architecture

An FSK/FMCW-capable K-Band VCO-transceiver, controlled through a tuning voltage (Vtune), provides 24GHz-24.250GHz transmit frequency according to the applied Vtune voltage, expressed in the present application by a continuous DC signal of 5V. The signal coming from the receiving antenna is demodulated and a set of two intermediate frequency signals (direct signal (I), quadrature signal (Q)) are obtained.

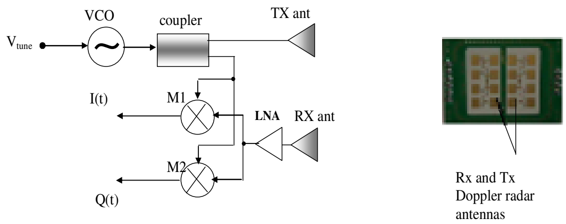


Fig. 2. FMCW Doppler radar motion sensor

The I and Q signals delivered by the microwave radars are acquired and processed in order to extract the gait pattern for the user during the rehabilitation period.

Fig. 3. Four wheels walker with 2 X FMCW Doppler radar motion sensors

B. Aquistion and wireless communication

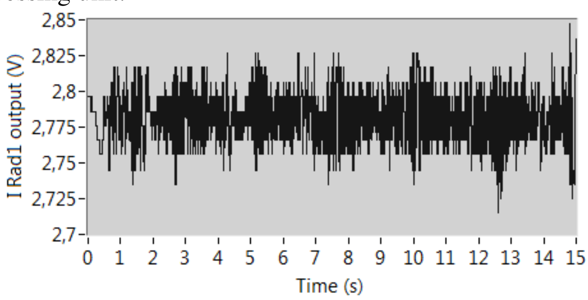
The Doppler radar sensor array is connected to the analog input channels of an NI WLS-9215 data acquisition and wireless communication module mounted on the walker's basket. The NI WLS-9215 is a combination of an NI WLS-9163 wireless carrier and an NI 9215 C Series measurement module. The WLS-9163 presents IEEE 802.11g wireless communication connectivity that was used to develop an Ad-Hoc wireless network including local processing, data storage and communication unit (Fig. 1: home physiotherapy client). Referring to the acquisition, the NI-9215, characterized by 4 analog inputs and 16 bit resolution, was remote programed to acquire the signals at 500 S/s acquisition rate. Considering the number of channels the system can acquire the I,Q intermediate frequency signals associated with two Doppler radar sensors of the walker.

III. GAIT SIGNAL PROCESSING

Taking into account that the human body is a complex object characterized by different rigid parts connected by joints, the gait during rehabilitation using the walkers represents a motion of swinging legs. The swinging of torso and arms that generally characterize the walking gait is not considered in this approach taking into account that the radars (maximum 2 radars one for each leg) are oriented to capture only the legs motion.

A. Signals

The radars signals captured by two radar of the four wheel walker are presented in Fig. 4. No analog processing was carried out, an important DC component being present in the acquired signals by the local acquisition and primary processing unit.



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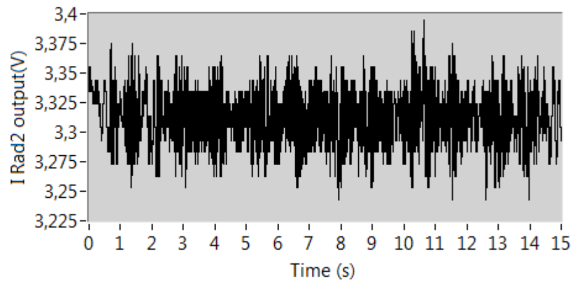


b)

Fig. 4. The signals captured by the microwave Doppler radar array for a regular walking of the walker user a) rad1 signal left side, b) rad2 signal right side.

The used radar transmits 24GHz and measures the shifts in the reflected waves that may be used to extract the information about the legs velocities in the radar sensor array's direction based on digital signal processing of Doppler radars acquired signals.

B. Spectrograms

The legs create a set of Doppler signatures during the walker usage, which can be highlighted through a spectrogram that is expressed by short-time Fourier transform (STFT) of the acquired radar signals. STFT provides time-frequency representation and is defined by:

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

where t is time, f is frequency, rad is the acquired radar signal and w is a sliding window function. According to the selected sliding window, the Doppler signatures spectrograms can be better highlighted. Thus, a practical approach concerning the usage of different sliding windows (e.g. Hanning, Hamming, Blackman) for motion signature extraction through radar signal spectrogram was carried out. Additionally, a Gaussian window was used in the STFT, this particular implementation being known as Gabor Transform that is defined by:

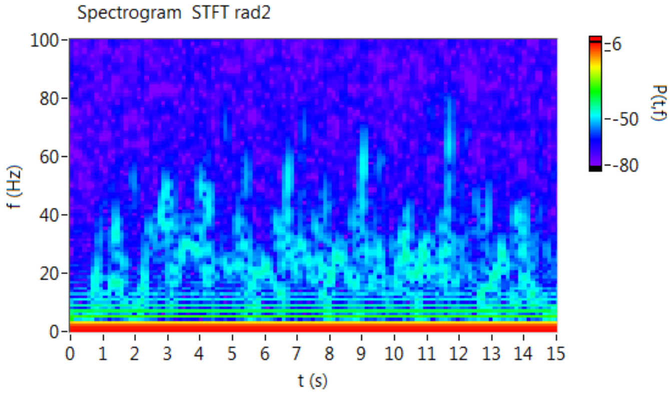
$$G(t,f) = \int_{-\infty}^{\infty} e^{-\frac{(\tau-t)^2}{2}} e^{-j2\pi ft} rad(\tau)d\tau \quad (2)$$

The Gabor Transform was chosen considering the characteristics of less leakage in time-frequency domain.

A set of spectrograms showing the Doppler signature of a walker user for a regular gait are presented in Fig. 5. Figure 5.a. presents the STFT spectrogram (Hanning window) and Fig. 5.b. presents a Spectrogram based on Gabor Transform. The horizontal axis represents time t, the vertical axis represents frequency f and the third axis shows the energy of the signal at certain time and frequency, P(f, t). Analyzing the above presented spectrograms may be underlined a set of peak energies that correspond to high frequencies caused by leg motions. At the same time can be observed a DC contamination that may be removed based on mean signal subtraction, the obtained spectrograms for no DC components being presented in Fig. 6. As it can be observed in that figure, Gabor Spectrogram better highlights the energy peaks associated with leg motion that after DC removal that may be used to extract the gait velocities but also the stride rate.

C. Gait velocity estimation

To estimate the gait velocities a spectrogram based analysis is carried out taking into account that the leg velocity corresponds to the frequency shift with the highest reflected energy [14].



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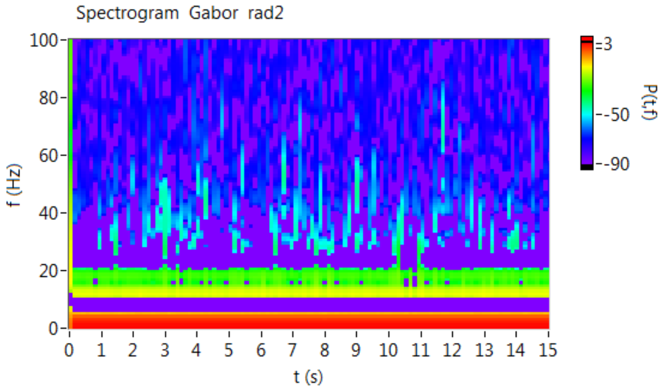


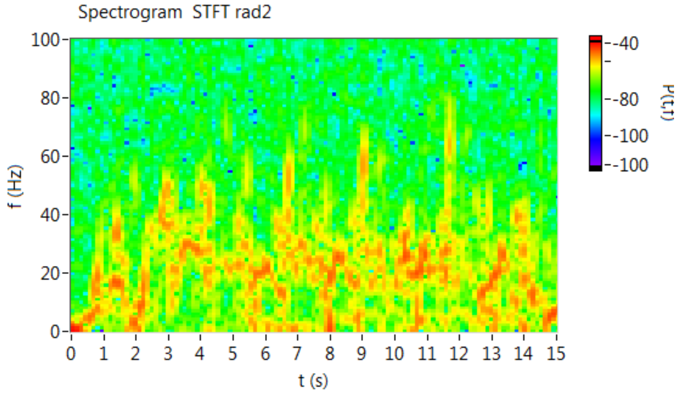
b)

Fig. 5. Doppler radar spectrograms for leg swing during walker usage: a) STFT spectrogram, b) Gabor Spectrogram

Analyzing the Fig. 6 spectrograms it can be observed the persistence of low frequency components caused by remained DC and multipath reflection during gait that are removed using wavelet processing of the acquired radars signals. This type of processing is an alternative method to the common band pass filtering reported in the literature [14][15] as part of walking velocity estimation algorithm where the lower and higher cutoff frequency are part of an iterative process. In the present case, the wavelet multiresolution analysis algorithm based on discrete wavelet transform (DWT) was used in two decomposition-reconstruction stages to perform the high frequency and low frequency filtering the DWT was not used to extract the gait velocity information. To implement the DWT, discrete filters banks were used to compute discrete wavelets coefficients, different level of decomposition (4 to 8) being considered. Using the *wavelet multiresolution express VI* a practical approach concerning the effects of the selected mother wavelets and sub bands on the reconstruction of the signal, for accurate gait velocity estimation. The spectrogram obtained for regular gait after wavelet processing using 4 level decomposition and db12 mother wavelets is presented in Fig. 7.

Considering the usage of the walker by people with limited walking capabilities, the expected velocities, expressed on the spectrograms by peaks of energy at f=100Hz, are lower than reported values of 2.4 m/s [15].

Considering the motion sensing based on the radar sensor array, the results obtained from rad1 and rad2 are compared considering the obtained gait velocities but also the time instants corresponding to the leg swings.



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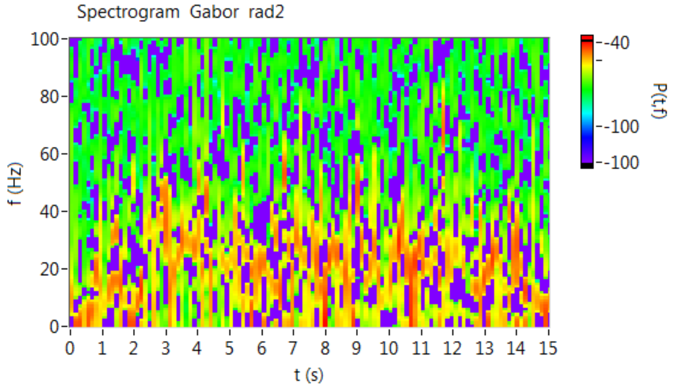

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Fig. 6. Doppler radar spectrograms for leg swing during walker usage after DC contamination removal: a) STFT spectrogram, b) Gabor Spectrogram

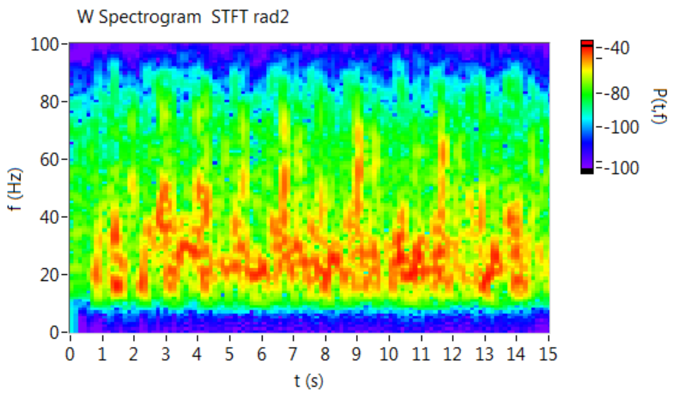


Fig. 7. Doppler radar spectrograms for leg swing during walker usage after wavelets based signal processing

Taking into account that the leg swings generates higher frequency shift but low reflected energy due to reduced radar cross-section area leading to low signal-to-noise ratio, accurate extraction of time instants of the leg swings was additionally obtained in three stages: i) median and moving average filtering of spectrogram at each time instant; ii) background noise subtraction; iii) time localization of peak energy using a peak detection algorithm for stride rate estimation.

D. *Regular and Abnormal Gait Features*

The usage or wheeled walkers with motion detection capabilities based on Doppler radar sensor array in the rehabilitation process may contribute to objective estimation of the rehabilitation progress. In this case, the right choice of features that may be used for better classification between abnormal and normal gait as well as to extract the tendency to normal or abnormal gait is an important issue. Based on a set of tests made with physiotherapists as walker users that simulate normal (regular) and abnormal (e.g. himiplagic gait), different features associated to time-frequency analysis (STFT and Gabor Spectrogram) of the acquired radar signals were calculated and several comparisons were done taking into account the type of performed gait. The main features calculated for the obtained spectrograms are the mean instantaneous frequency defined by

$$f_{mc} = \frac{\int_0^\infty f P(t,f) df}{\int_0^\infty P(t,f) df} \tag{3}$$

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

$$\Delta f_{mc} = \sqrt{\frac{\int_0^\infty (f - f_{mc})^2 P(f) df}{\int_0^\infty P(f) df}} \tag{4}$$

A comparison between the values of spectrogram features for different normal and abnormal gait was carried out.

IV. Results and Discussions

The purpose of this work is to evaluate the capabilities of microwave Doppler radar embedded in wheeled walker in assessing human gait during rehabilitation. A time-frequency analysis software module was implemented on the server side the system to extract characteristics of normal and abnormal gait. The gait signals were obtained in this stage from healthy volunteers that perform normal but also abnormal gait for normal speed, slow speed and faster speed for a limited period of time or for an imposed distance (4m). STFT and Gabor Spectrograms were used to extract gait characteristics such as velocities or leg swing instances making comparison between different calculated features associated with normal and abnormal gait. For the particular case of normal gait (right-left-right leg sequence) and abnormal gait (left-left leg sequence and right-right sequence) the STFT spectrograms of the rad1 and rad2 radar signals indicate the low velocity and also low stride rate.

The presented spectrograms corresponds to the signals obtained after DC component extraction and wavelet processing using 4 level decomposition and db04 mother wavelet.

As it can be observed in Fig. 8 different types of walking are characterized by distinct Doppler radar signatures captured by the rad1 and rad2 corresponding to the left side and right side of the walker user. At the same time, the regular left-right leg walking implies higher reflected energy than in the anomalous gait cases.

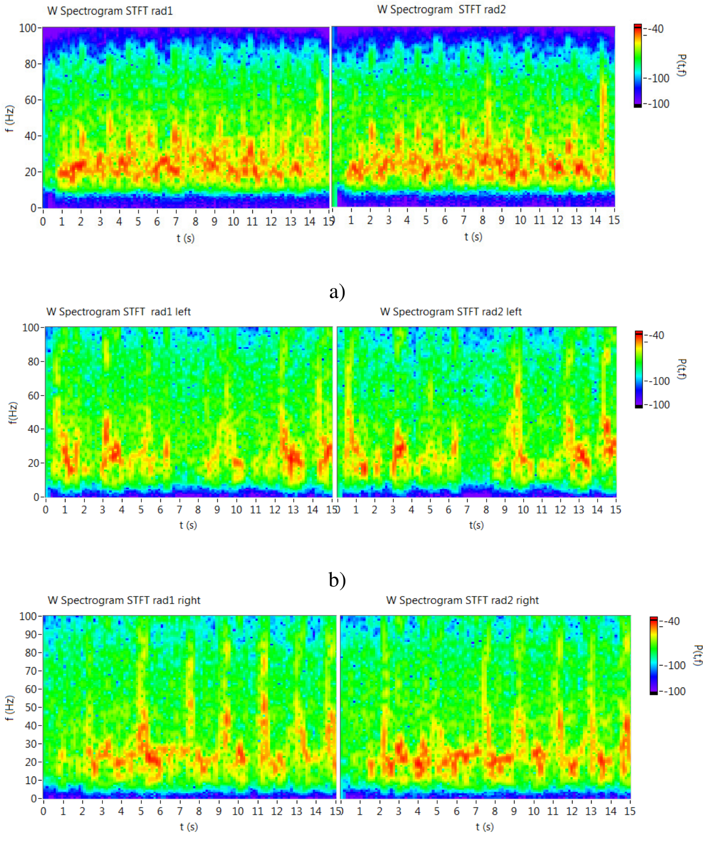


Fig.8. STFT spectrograms for slow walking gait supported by a) left-right leg, b) left leg and c) right leg

Regarding the gait velocity estimation for normal and abnormal analysis, a set of wavelet processed STFT and Gabor spectrograms were used. The evolutions of the speed for normal slow gait and abnormal slow gait are presented in Fig. 9 and Fig. 10.

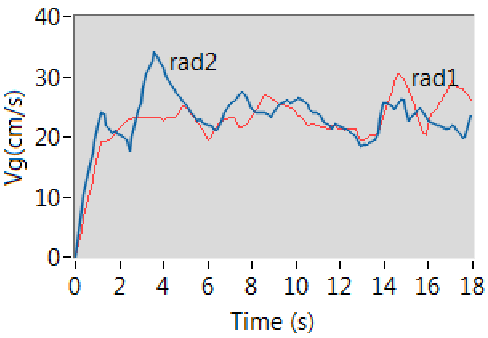
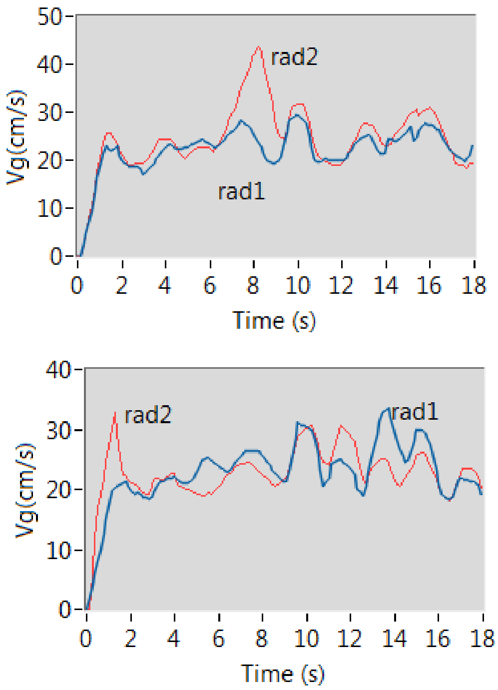


Fig.9. STFT spectrograms for slow walking gait supported by a) left-right leg, b) left leg and c) right leg

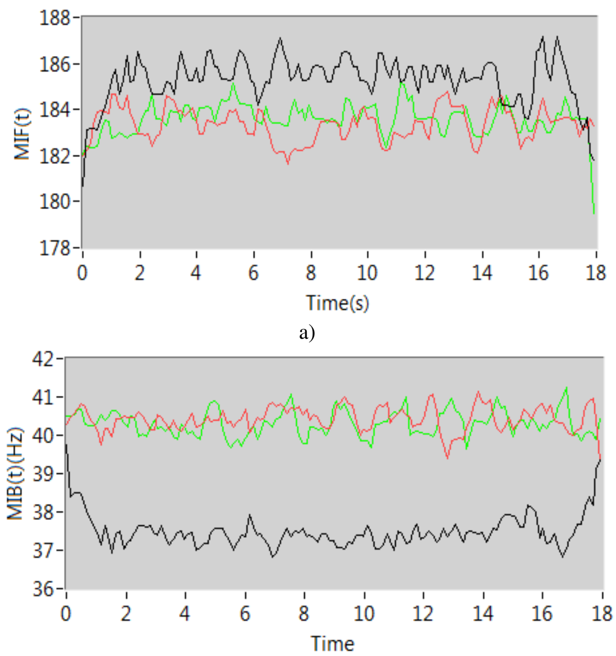


b)

b)

Fig.10. Abnormal gait velocity evolution a) abnormal left-left leg gait, b) abnormal right-right leg gait

Referring to normal and abnormal gait detection, the features calculation for radar signature spectrograms were carried out. In Fig. 11 is presented the evolution of mean instantaneous frequency and mean instantaneous bandwidth spectrogram features for several tests characterized by normal and abnormal gait walker user.



a)

b)

Fig.11. The evolution of: a) mean instantaneous frequency (MIF) and b) mean instantaneous bandwidth (MIB) for normal (black line) and abnormal gait (left-left: red line, right-right: green line) of walker user

As it can be observed in Fig. 11, the chosen features discriminate well between the normal and abnormal gait. However, it is difficult to extract information about the type of abnormal gait. Additional studies will be done in the future.

V. Conclusion and Future Work

The designed and implemented walker and the implemented client-server architecture that uses walkers with gait sensing based on FMCW Doppler radars and wi-fi wireless communication proves to be a good solution for gait characterization of the walker users. The sensing unit can be easily adapted to other types of walkers generally used in gait rehabilitation such standard or two wheels walkers. Referring to gait signal processing is underlined a novel approach based on the use of wavelet multiresolution analysis for the estimation of gait velocity and of the time instants corresponding to the leg swings.

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